APPENDIX C

VADOSE ZONE CONCEPTUAL MODEL

APPENDIX C

Vadose Zone Conceptual Model Abstract

The objective of this appendix is to describe the vadose zone conceptual model developed for use in the System Assessment Capability (SAC), Rev. 0.

Output from the vadose zone technical element will provide estimates of contaminant flux to the groundwater from various waste sources on the Hanford Site to allow feasibility testing of the SAC (Rev. 0) and to complete an initial assessment of risk and impact from Hanford Site waste. The data from this element feed into the groundwater technical element (Figure C-i).

The vadose zone technical element will take the results of the analyses from the release technical element in the form of spatial and temporal contaminant flux to the ground at the surface or near subsurface. In addition to the contaminant flux from the release element, the vadose zone model requires data that define the physical characteristics of the sediments present between the ground surface and the water table, chemical characteristics of the sediments and contaminants, natural and artificial recharge at or near the ground surface, and subsurface transformation processes.

Definition of the physical characteristics of the sediments at the various source areas will be based on previous subsurface investigations that have collected data on the geologic/hydrologic units, unit boundaries, moisture content relationships, and composition. Water table elevation data and changes over time are also critical data for definition of the vadose zone thickness and the length of the resulting transport pathway. Water table elevation data will be provided from direct measurements that have been taken regularly on a site-wide basis. Chemical characteristics of the sediments and the contaminants will be provided from site-specific work done by previous investigations and from information provided in published sources.

Critical data to the vadose zone element also include estimates of sorption and desorption of contaminants to sediments, oxidation-reduction reactions, radioisotope decay rates, dispersivity, and complexing chemical reactions that could affect contaminant mobility. These data will be taken primarily from published references for the SAC (Rev. 0) demonstration.

Data from the vadose zone element will include estimates of the spatial and temporal distribution of contaminant flux to groundwater. Estimates of contaminant flux for four classes of radionuclides and two chemicals of concern will be provided as input data to the groundwater model element. Contaminant flux to the groundwater will be estimated based on conditions representative of the aggregated waste sites. Output from the vadose zone model provided to the groundwater element will reflect the impact of aggregating waste type and waste location as described in the inventory and release conceptual models, as well as the result of generalizing the vadose zone for the aggregated waste site locations. The areal extent of the region aggregated will be based on input requirements and historic knowledge of groundwater flow pathways that have been delineated by the groundwater monitoring well network in place on the Hanford Site.

Verification of the estimated contaminant flux to groundwater will be made by comparing estimates of contaminant flux to the extent of contaminant distribution observed in groundwater through groundwater monitoring.

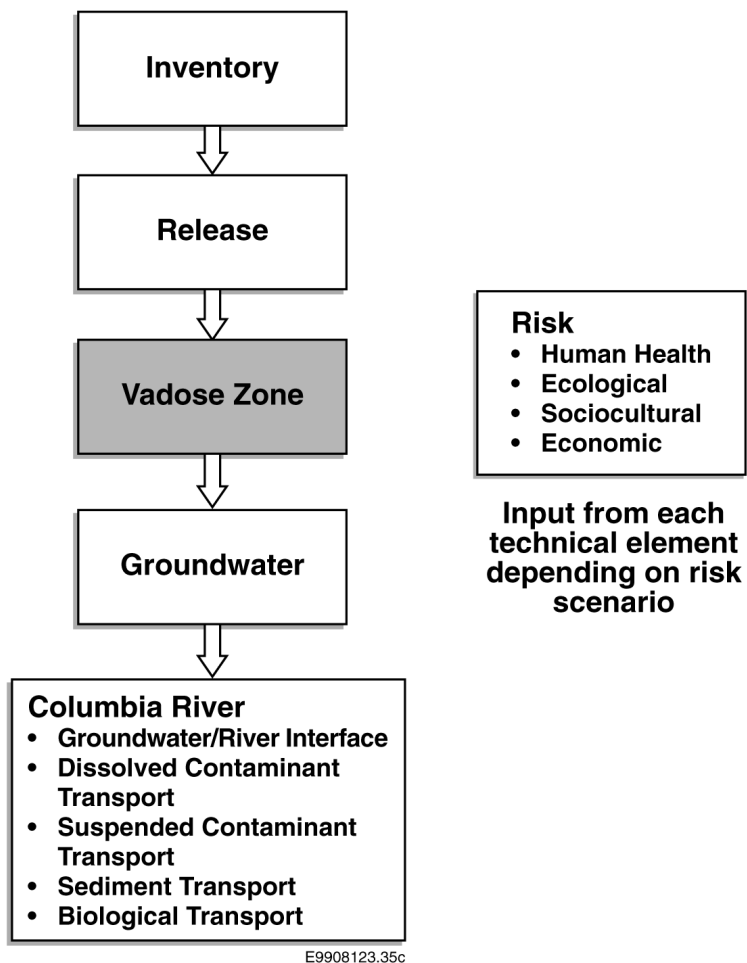**Figure C-i. System Assessment Capability System Conceptual Model.**

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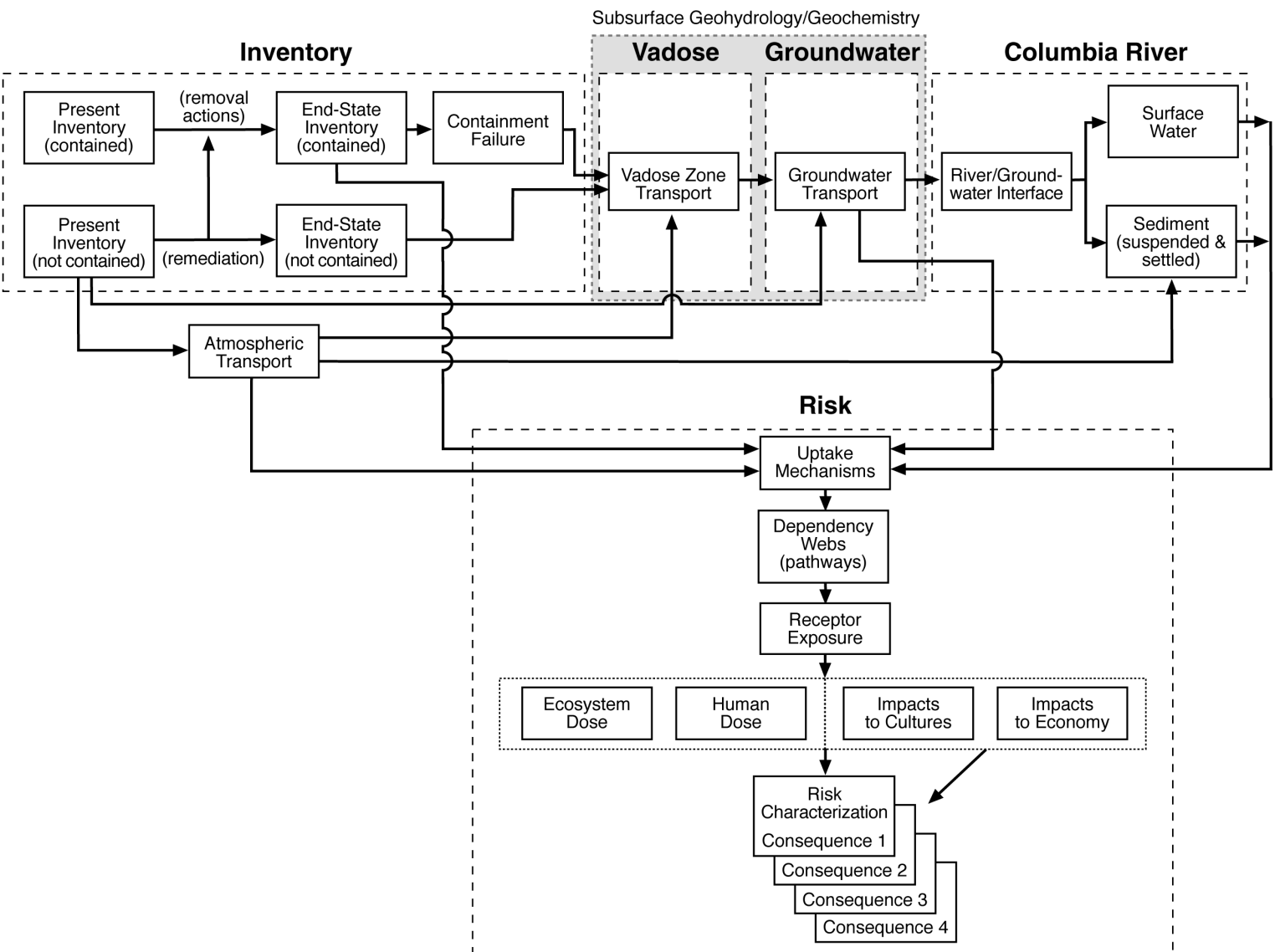# VADOSE ZONE CONCEPTUAL MODEL

C.1   BACKGROUND

The objective of this white paper is to describe the conceptual models of vadose zone flow and transport to be represented in the System Assessment Capability (SAC) (Rev. 0). This is one of several white papers describing conceptual models for various technical elements of the SAC. Other white papers include those on inventory, waste release models, groundwater, river, and risk.

The vadose zone is the hydrogeologic region that extends from the soil surface to the water table (DOE-RL 1998b). The geographic focus is on areas at the Hanford Site that 1) underlie liquid waste disposal sites and tanks; 2) have the potential for leaks or leaching; and 3) have experienced past leaks and spills. Selected areas away from the focus areas are also included (i.e., areas representative of background conditions, and areas that have the potential to become contaminated in the future).

Figure C-1 illustrates a general system conceptual model for the SAC, as presented in the *Groundwater/Vadose Zone Integration Project Specification* (DOE-RL 1998b). Figure C-1 illustrates the role of the vadose zone technical element and its primary linkages with other technical elements. The vadose zone element relies on input from the inventory and release elements. This needed input includes the spatial and temporal distributions of waste releases and the mass flux and concentrations of these releases. Other required inputs would come from existing databases and/or future predictions/operational plans. These plans would include infiltration rates from both natural events (e.g., precipitation, snow melt run-on) and operational activities (e.g., pipe leaks, dust suppression, sanitary discharges), the effectiveness and timing of planned remedial activities (e.g., excavation, capping, soil vapor extraction), and the hydrostratigraphy and associated physical and chemical parameter distributions. Output from the vadose zone element would feed the groundwater and/or the risk elements. This output would be primarily in the form of spatial and temporal distributions of the mass flux and concentration of contaminants.

Wilson et al. (1995) describe flow within the vadose zone as dynamic and characterized by periods of unsaturated flow at varying degrees of partial saturation punctuated be episodes of preferential, saturated flow in response to hydrologic events or releases of liquids. Specific topics of interest to the Hanford Site include 1) subsurface contamination (i.e., characteristics of past disposal and leakage, including chemistries, volume, and distribution); 2) surface hydrologic features and processes (e.g., winter rain and snowmelt, water line leaks, infiltration, deep drainage, and evaporation rates); and 3) subsurface geologic and hydraulic features and processes (e.g., stratigraphy, structures, physical properties, geochemistry, and microbiology of the sediments above the water table) (DOE-RL 1998b).

Subsurface Geohydrology/Geochemistry

Inventory

Vadose **Groundwater**

Columbia River

Present Inventory (contained)

(removal actions)

End-State Inventory (contained)

Containment Failure

Vadose Zone Transport

Groundwater Transport

River/Ground-water Interface

Surface Water

Present Inventory (not contained)

(remediation)

End-State Inventory (not contained)

Sediment (suspended & settled)

Atmospheric Transport

Risk

Uptake Mechanisms

Dependency Webs (pathways)

Receptor Exposure

Ecosystem Dose

Human Dose

Impacts to Cultures

Impacts to Economy

Risk Characterization

Consequence 1

Consequence 2

Consequence 3

Consequence 4

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Figure C-1. System Assessment Conceptual Model Diagram.

Conceptual models are evolving hypotheses that identify the important features, events, and processes controlling fluid flow and contaminant transport at a specific field site and in the context of a specific problem. The conceptual model is a key initial element in the overall modeling process. Once the site-specific problem is defined and the important features, processes, and events conceptualized, quantitative descriptions can be prepared and implemented. Field data are then used to both calibrate and independently test the predictive capabilities of the model.

Kincaid's *Candidate Sets Report*[1] provides a comprehensive compilation of the 1) features (the structure and transport properties of the various pathways), 2) events (e.g., recharge, source releases, etc.), and 3) processes (the fate and transport processes/mechanisms, including driving forces) considered relevant to contaminant flow and transport within the vadose zone beneath the Hanford Site. Figure C-2 illustrates some of the primary conceptual model concepts.

C.2   PAST PROJECT/EXISTING CONCEPTUAL MODELS

Past vadose zone conceptual models are described through various studies that were performed at the Hanford Site. Hundreds of documents have been produced during the last 50 years on various aspects of the vadose zone. This section highlights some of these key studies.

C.2.1   Previous Studies

Low-level and intermediate-level radioactive liquid wastes were discharged to the vadose zone sediments since the startup of Hanford Operations (Brown and Rupert 1948). This approach to waste disposal was based on available data suggesting that the sorptive capacity of the soils would retain the radioactivity. This, in turn, would permit the decay of a majority of the radioactivity and allow the decontaminated solution to percolate to the groundwater. This disposal philosophy prompted extensive investigations into the geologic, hydrologic, and sorptive characteristics of the Hanford Site sediments (Parker and Piper 1949; Brown and Rupert 1948; Brown and Rupert 1950; Brown 1959; Hajek 1965; Routson 1974; Tallman et al. 1979; Routson et al. 1981; Graham et al. 1981; DOE 1998; Last et al. 1989; Connelly et al. 1992a, 1992b; Hartman and Peterson 1992; Lindsey 1992; Lindsey et al. 1992a, 1992b; DOE-RL 1992a, 1992b, 1992c, 1992d; DOE-RL 1993a, 1993b, 1993c, 1993d, 1993e; Thorne et al. 1993, 1994; Reidel and Fecht 1994a, 1994b; Khaleel and Freeman 1995a, 1995b; Peterson et al. 1996; Reidel and Horton 1999; Fecht et al. 1999). After 1955, the volume of radioactive wastes discharged to the ground was locally minimized because of the detection of contaminants in the groundwater (Tallman et al. 1979), environmental investigations turned toward natural recharge and unsaturated water flow (Last et al. 1976, Jones 1978, Gee 1987, Gee et al. 1992), and evaluation of various waste disposal sites (Haney and Linderoth 1959, Smith 1973, Fecht et al. 1977, Routson et al. 1979, Price et al. 1979, Smith 1980, Marratt et al. 1985, Last et al. 1994, Rohay et al. 1994). In the 1980s and 90s, scientists focused on the design of surface covers (Fayer et al. 1985, Gee et al. 1994) to control infiltration, erosion, and intrusion.

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[1] Kincaid, C. T. et. al. June 25 1999. Candidate Sets Report.

Figure C-2. General Vadose Zone Conceptual Model Concepts.
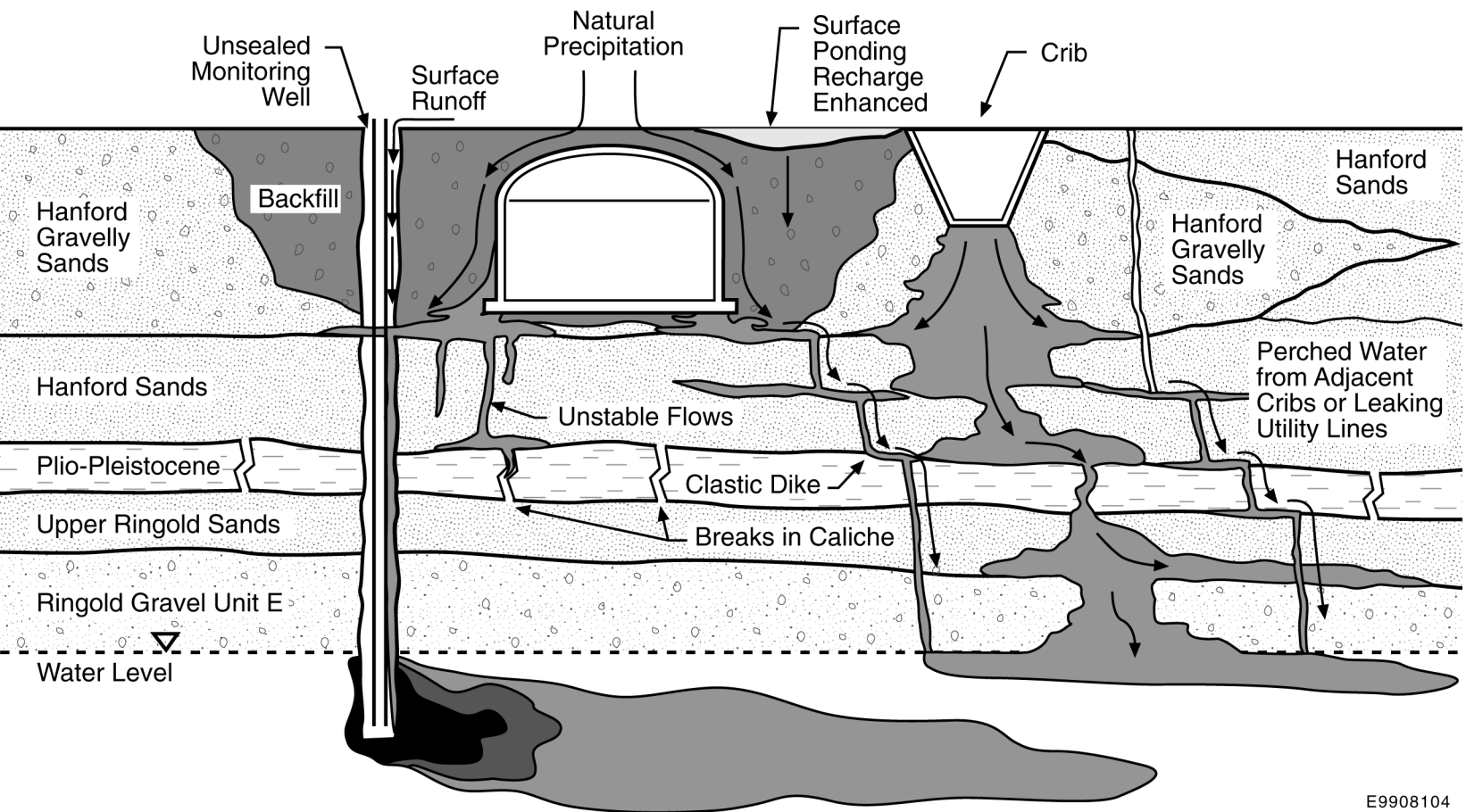
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Appendix C – Vadose Zone Conceptual Model

In the mid-1970s, several retired 200 Area liquid-waste disposal sites were characterized to determine radionuclide distributions in sediments surrounding the facilities. The U.S. Department of Energy (DOE) (1987) reviews these studies and provides insight into the behavior of radionuclides in the Hanford Site subsurface environment. These characterization studies included four cribs (216-A-24 [Klepper et al. 1979], 216-Z-12 [Kasper 1981a, 1981b, 1982], 216-Z-1A [Price et al. 1979], and the 216-S-1 and 216–S-2 [Van Luik and Smith 1982]); a trench (216-Z-9 [Price and Ames 1975]); a french drain (216-Z-18 [Marratt et al. 1985]), a reverse well (216-B-5 [Smith 1980, 1981]); a disposal pond and ditch system (216-U-10 Pond and 216-Z-19 Ditch [Last et al. 1994]), and high-level waste tank leak (241-T-106 [Routson et al. 1979]).

C.2.1.1. 216-A-24 Crib. Characterization data from the 216-A-24 Crib (that received boiling tank condensate) found that the gravel bed of the drain field retained significant amounts of cesium-137, while the soils above the polyethylene sheet overlying the gravels were uncontaminated. However, detectable concentrations of cesium-137 were found in the roots of rabbitbrush growing over the site and in the upper 1 cm of soil and litter beneath the canopies of these plants.

C.2.1.2. 216-Z-12 Crib, 216-Z-1A Tilefield, and 216-Z-9 Trench. Studies of the 216-Z-12 Crib (that received "low-salt" transuranic waste) found that the highest concentration of plutonium (Pu) occurred immediately below the crib bottom and decreased rapidly to a depth of 12 to 30 m. Low-level Pu and americium (Am) were detected to depths of 30 to 36 m, retained in a fine-grained silt layer. At 216-Z-1A (that received high salt acidic transuranic waste, as well as CCl_4 organic wastes), Price et al. (1979) found that the highest concentrations of Pu and Am were within the first 3 m beneath the crib bottom and decreased with depth, except for silt-enriched horizons and boundary areas (contacts) between major sedimentary units. The maximum vertical penetration of actinides was to a depth of 30 m, and the maximum lateral extent was within a 10-m wide zone slightly larger than the perimeter of the crib. Price et al. (1979) considered the primary transport/distribution mechanisms to include filtering of Pu oxide particles, the effect of unsaturated flow, and changes in pH produced by silicate hydrolysis and/or neutralization by calcium carbonate ($CaCO_3$).

Studies of the 216-Z-9 Trench produced similar results with high concentrations of Pu immediately beneath the bottom of the trench decreasing rapidly with depth. The high concentrations immediately beneath the trench bottom were attributed to 2 to 25 µm diameter Pu oxide particles that were filtered by the sludge and sediment in the bottom of the trench. "Non-particulate" Pu was observed to a depth of 2 m where it sorbed or precipitated out, at least partially in conjunction with silicate hydrolysis reactions between the acidic waste and the sand-to silt-sized rock fragments.

C.2.1.3. 216-S-1 and 216-S-2 Cribs. Studies of the 216-S-1 and 216-S-2 Crib (that received acidic [pH=2.1] high salt waste from Redox) found that 90% of cesium-137 was adsorbed by the soil while less than 10% of the strontium-90 was adsorbed, due to the low pH and high salt concentrations of the waste. Most of the cesium-137 was retained within the top 10 m beneath the crib, while strontium-90 migrated to the water table, due, in part, to a failed well casing.

C.2.1.4. 216-B-5 Reverse Well. Characterization of the 216-B-5 Reverse Well (that injected low-salt, alkaline wastes directly into the groundwater) found that the distribution of cesium-137 was influenced by a silty layer 78 m below ground surface and the historic 1948 water table. The distribution of strontium-90 and cesium-137 was more widespread than Pu (for which little migration was observed) due to their increased mobility. However, the zone of contamination around the reverse well was stable, with no apparent further migration after retirement of the facility.

C.2.1.5. 216-U-10 Pond and 216-Z-19 Ditch. Studies of the 216-U-10 Pond and 216-Z-19 Ditch system found that the large volumes of water discharged significantly raised the water table and created numerous perched water zones, but did not adversely impact the quality of the groundwater. Fission products and uranium were well distributed throughout the disposal system, while Pu and Am were localized closer to the points of discharge. Past decreases in the pond-water level resulted in exposure and drying out of the surface contamination around the pond, providing a source from which atmospheric resuspension of strontium, cesium, Pu, and Am occurred. The ecological system that developed around U-pond provided the means for biological transport away from the pond.

C.2.1.6. 241-T-106 Tank Leak. Studies of the 241-T-106 Tank Leak found zonation of the contaminants, with ruthenium-106 moving farther than, cesium-137, which moved farther than cerium-144. Routson et al. (1979) found that essentially all detectable ruthenium-106 movement occurred within the first year after the tank leak; a large portion of the cesium-137 movement was also thought to have occurred within the first year. The maximum extent of ruthenium-106 contamination was found to a depth of 33 m.

C.2.1.7. 216-U-1 and –2 Cribs. DOE (1987) and DOE-RL (1998b) indicated that perched water beneath a nearby active crib (216-U-16) was diverted horizontally perhaps 100s of meters by the caliche unit, where it contacted uranium-contaminated soils beneath the U-1 and U-2 Crib and migrated down the unsealed annulus of at least one well. The acidic nature of the U-1 and U-2 wastes (and the presence of high concentrations of $CaCO_3$) led to the formation of an anionic uranium carbonate complex that was not sorbed by the soil.

C.2.2 Numerical Assessments

Scientists have studied and attempted to predict the flow of water and radionuclides in the Hanford Site soils since early site operations. Numerical models have been used to predict water flow in the unsaturated sediments since the early 1960s (Reisenauer 1963). Fayer et al. (1986) presented a summary of early unsaturated-flow model development at the Hanford Site.

Radionuclide transport modeling has been conducted since the early 1970s (Routson and Serne 1972). Jones and Gee (1984) presented a summary of hydro-geochemical processes controlling radionuclide transport and the mathematical models used to describe those processes (Figures C-3 and C-4). Recent developments were helpful in identifying key and controlling physical processes affecting transport of contaminants (Smoot and Sagar 1990; Huyakorn and Panday 1994; White and Oostrom 1996a, 1996b; Nichols et al. 1997; Ward et al. 1997).

Figure C-3. Summary of Hydro-Geochemical Processes Controlling Radionuclide Transport (Jones and Gee 1984).
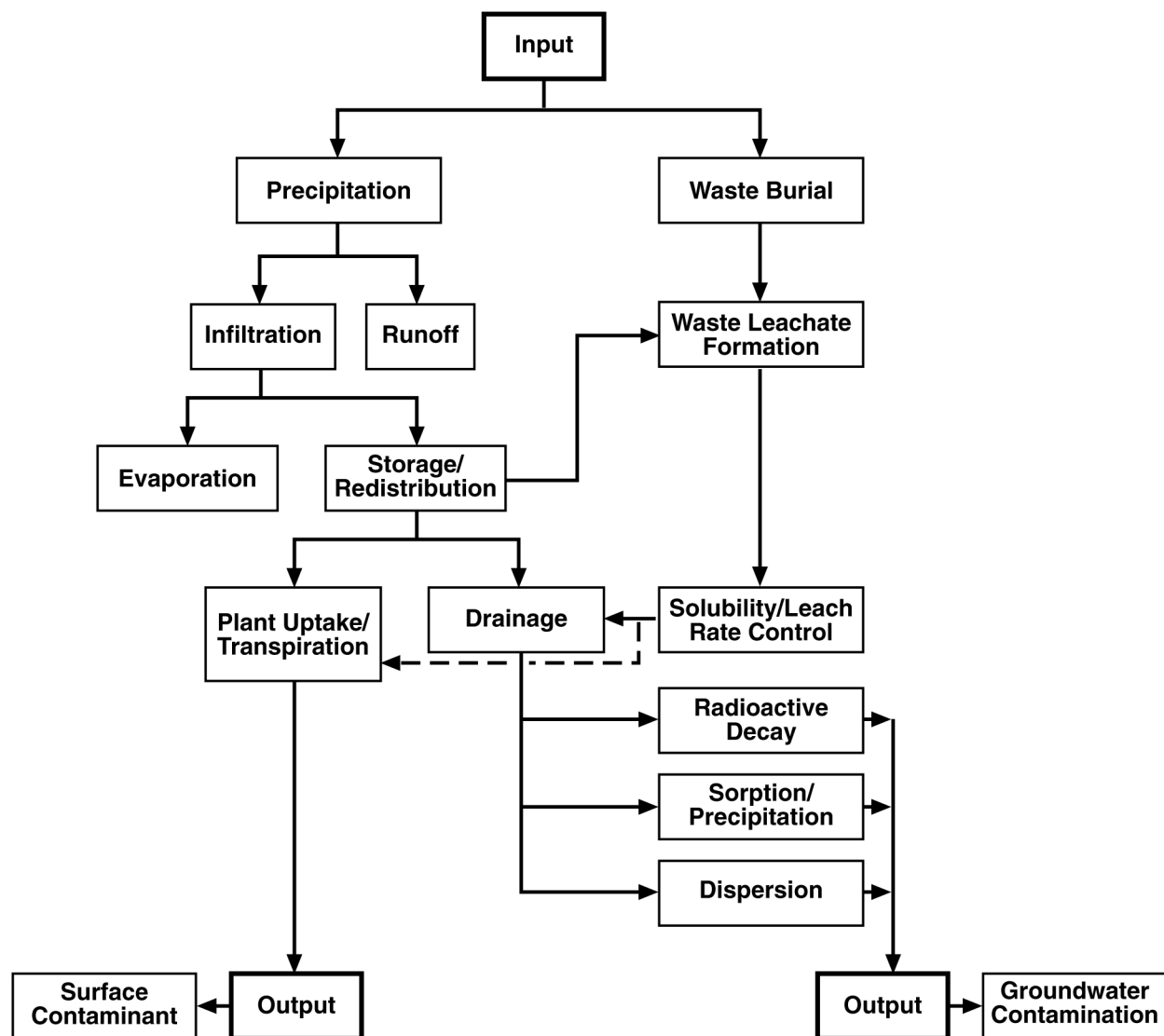
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Figure C-4. Summary of Transport Models and Their Data Requirements, Used to Predict Unsaturated Zone Transport (Jones and Gee 1984).

*PET = POTENTIAL EVAPOTRANSPIRATION

**PE = POTENTIAL EVAPORATION

***LAI = LEAF AREA INDEX
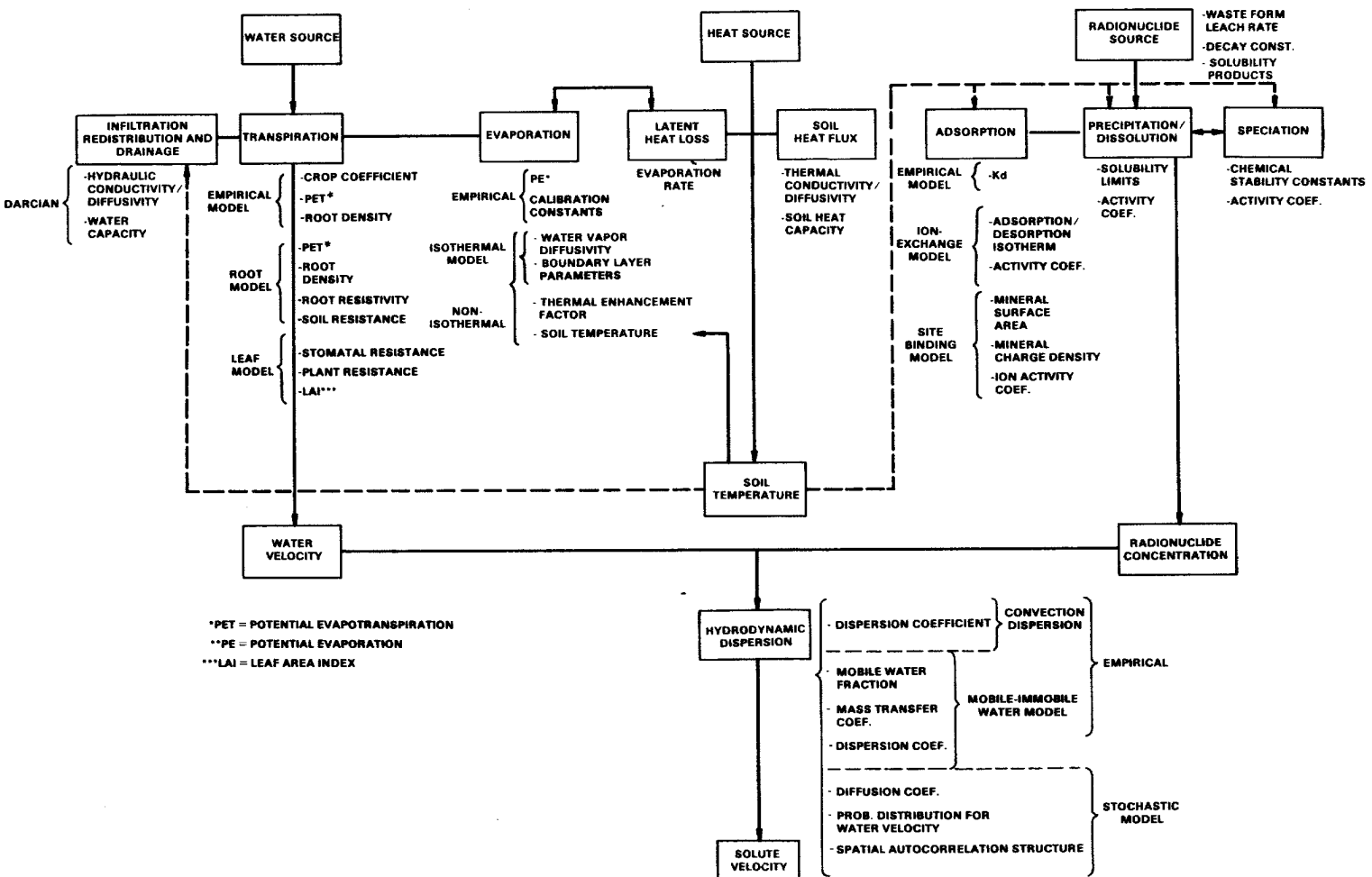
Appendix C – Vadose Zone Conceptual Model

Many project-specific performance assessments were conducted to assess contaminant migration rates in the vadose zone (Bergeron et al. 1987; DOE 1987; DOE 1993; DOE-RL 1994; Rhoads et al. 1994; Wood et al. 1995, 1996; Mann et al. 1998; Jacobs Engineering Group, Inc. 1998a, 1998b, 1999; Kincaid et al. 1995, 1998). The individual project-specific transport-models used in these assessments were configured in an ad hoc way, on a site-specific basis, to evaluate specific problems and solutions. These models varied in dimension (1-D vs. 2-D vs. 3-D) and complexity (e.g., number of hydrogeologic units, isothermal vs. non-isothermal, steady state vs. transient, etc.).

Recent important studies addressing the implications of single-shell tanks (SST) and other performance assessments include the following:

- The Composite Analysis (Kincaid et al. 1998)

- The AX and SX Tank Farm vadose zone screening analyses for the Hanford Tanks Initiative (HTI) (Jacobs Engineering Group, Inc. 1998a, 1998b)

- The RCRA Phase I Assessment Reports for the S-SX, T, TX-TY, and B-BX-BY waste management areas (Johnson and Chou 1998, Hodges 1998, and Narbutovskih 1998), the Tank Waste Remediation System (TWRS) vadose zone expert panel report (DOE 1997)

- The PNNL contaminant transport analysis beneath SST SX-109 (Ward et al. 1997)

- Hanford low-level tank waste interim performance assessment (TWRS ILAW PA) (Mann et al. 1997, 1998)

- TWRS analysis (DOE and Ecology 1996)

- Ongoing 2-D and 3-D modeling activities being conducted as part of the HTI (Jacobs Engineering Group, Inc. 1999).

Recent studies specifically addressing vadose zone transport from tanks, used or alluded to the source and pathway conceptual model presented by Caggiano (1996) and shown in Figure C-5.

A summary of the conceptual model representations used in some of the more recent assessments and existing projects is presented below, along with some of the lessons learned.

**Figure C-5. Hypothetical Sources and Potential Pathways to Groundwater
in the S-SX Waste Management Area (Caggiano 1996).**
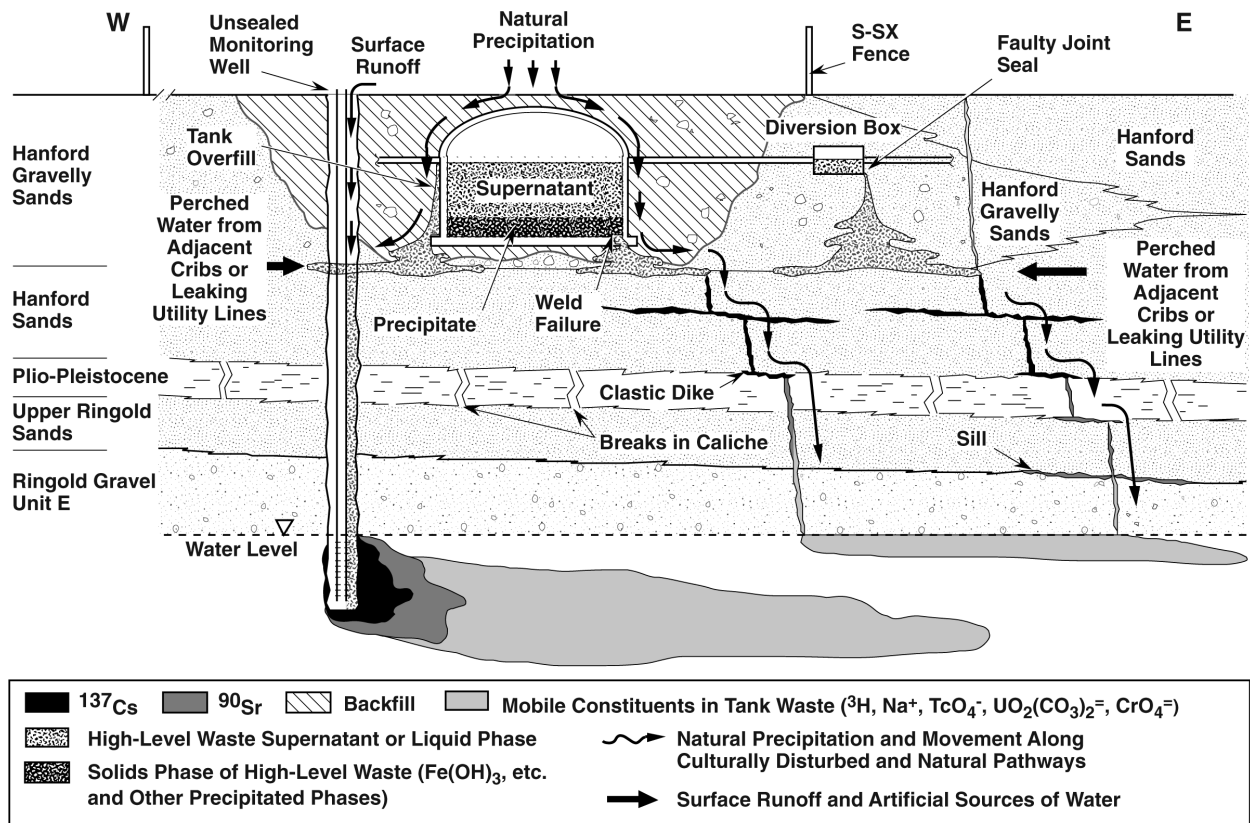
C.2.2.1. 200-BP-1. Liquid effluent migration at 200-BP-1 was modeled for tributylphosphate (TBP), cesium-137, cobalt-60, nitrate, strontium-90, technetium-99, Pu, and uranium (U) using a 2-D model (DOE 1993). Four scenarios were considered, with three scenarios modeling migration from a single crib source, but with varying (1 to 23 cm/yr) meteoric infiltration rates and one scenario modeling potential lateral migration of liquid effluent between the Cribs 216-B-43 through 216-B-50.

The modeled stratigraphy consisted of four layered-cake formations (Hoffman 1992), with the soils ranging from silt to sandy gravel. The stratigraphic units were assumed to be homogeneous and isotropic. Hydraulic properties for the modeled layers were derived from laboratory measurements of core samples from boreholes drilled at the site. Van Genuchten (1980) and Mualem (1976) models were used to represent moisture retention and unsaturated conductivity relationships.

An assumed meteoric recharge rate of approximately 23 cm/yr was used. The unusually large recharge rate (based on numerical simulations reported in Smoot et al. [1989]) was considered appropriate because the purpose of evaluating the scenario was to provide overly conservative estimates of contaminant migration within the vadose zone. For transport calculations,
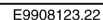
longitudinal and lateral dispersivities of 1 m and 0.1 m were used. A linear sorption isotherm model was used, and K_d values were based on information in Ames and Serne (1991) and Cantrell and Serne (1992).

C.2.2.2. RCRA Phase I Assessments of Single-Shell Tank Waste Management Areas. Some of the more recent descriptive studies concerning the conceptual understanding of flow and transport within the vadose zone include those associated with the S, SX, T, TX-TY, and B, BX, BY Tank Farms (Johnson and Chou 1998, Myers et al. 1998, Hodges 1998, Narbutovskih 1998). Pictorial representations of the conceptual model for the various possible soil pathways (from potential sources to the groundwater in a simplified geologic cross section) are shown in Figures C-6 and C-7 for the BX-BY and S-SX Waste Management Areas, respectively. An important aspect of these conceptual models was that the tank leaks provided insufficient driving forces to move even the most mobile constituents directly to the groundwater over the observed timeframe. Thus, other possible driving forces were examined, including operational spills and leaks from water mains, transfer lines and sewer lines, surface water spills, enhanced recharge due to coarse gravel cover and snowmelt/run-on, or preferential flow along borehole casings. Interfaces between fine- and coarse-grained geohydrologic units are expected to contribute to lateral spreading, and the topography of these interfaces is expected to control the direction of movement. These studies also assumed that the chemical and physical process affecting the waste would alter the basic chemical signatures of the waste in understandable ways, making it possible to distinguish various contaminant sources. Natural preferential flow paths (e.g., interconnecting clastic dikes, fingering, breaks in the caliche unit) are expected to have the potential to provide short-circuit pathways.

C.2.2.3. Contaminant Transport Beneath SX-109. Ward et al. (1997) used a 2-D model to explore various processes controlling contaminant migration in the vadose zone beneath the SX Tank Farm, and to determine the dominant processes and critical parameters controlling the model results. Both a simple uniform thickness-layered stratigraphic model, as well as a detailed stratigraphic model based on one by Price and Fecht (1976), were used in this study. Structural preferential pathways were not included. Hydraulic properties for the various strata were taken from Connelly et al. (1992a), fitted to determine their Brooks and Corey (1966) parameters, in conjunction with a Burdine (1953) relative permeability model. Ward et al. (1997) also included a fixed anisotropic ratio (kx/kz) of 1.5 for each geohydrologic unit. Four different recharge schemes were used, ranging from 0.5 mm/yr to represent the Hanford Barrier, to 100 mm/yr for a coarse gravel surface cover. A time-varying K_d approach was used to account for the geochemical effects related to the high pH and high sodium concentrations in fluids leaked from the tank. Four different K_d values for cesium-137 (ranging from 0 to 37 ml/g) were applied at selected times and durations.

This study clearly illustrated that density effects significantly increase the vertical mobility of both the fluid and contaminant, elongating the plume vertically and decreasing the lateral spreading. This study also demonstrated that increased complexity in the stratigraphic layering details gives rise to a more complex water-content distribution and enhanced lateral spreading that acts to impede vertical migration. The effects of the weak 1.5 anisotropic ratio within the geohydrologic units further increased spreading at the fine-grained/coarse-grained layer interfaces and enhanced downslope movement of the plume along these interfaces.

**Figure C-6. Conceptual Model Developed for WMA BX-BY
(Narbutovskih 1998).**

**Figure C-7. Conceptual Model Developed for WMA S-SX
(Johnson and Chou 1998).**

Legend:
^{137}Cs | ^{90}Sr | Backfill | Mobile Constituents in Tank Waste (^3H, $Na^+ \rightarrow Ca^{++}$, TcO_4^-, $UO_2(CO_3)_2^=$, $CrO_4^=$, NO_3^-)

High-Level Waste Supernatant or Liquid Phase | Natural Precipitation and Movement Along Culturally Disturbed and Natural Pathways

Solids Phase of High-Level Waste ($Fe(OH)_3$, etc. and Other Precipitated Phases) | Surface Runoff and Artificial Sources of Water
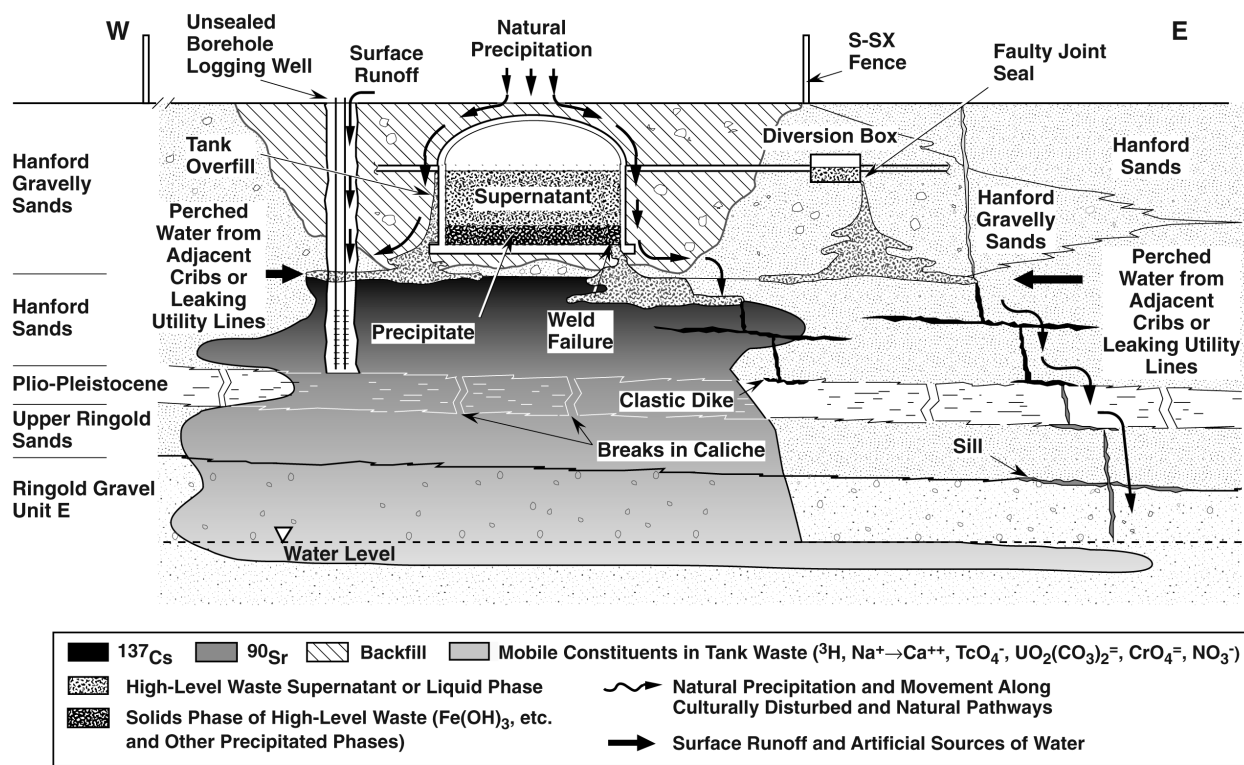
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They also illustrated the importance of chemically enhanced mobility. Ward et al. (1997) also found that the water flux between tanks ranged between 1.8 and 4.6 times the natural flux due to the umbrella effect that vectors recharge water off of the impermeable tank domes into areas between the tanks. In an analogous manner, a moisture-deficient zone is created beneath the tank, and increased capillarity helps the shedded water redistribute more uniformly once it has passed the tank bottoms. This study also illustrated the importance of accounting for the temporal nature of recharge. In dry environments, deep vadose zone flow (recharge) is typically controlled by the extreme events (e.g., snow melt and run-on events) that can result in a saturated or nearly saturated state corresponding to when preferential flow paths dominate the system behavior.

C.2.2.4. TWRS Expert Panel Findings. The ultimate purpose of the TWRS Expert Panel was to evaluate the conceptual models for cesium-137 transport beneath the SX Tank Farm, particularly with regard to whether cesium-137 may have migrated down poorly sealed boreholes, and/or directly through the formation. This panel hypothesized that the likely mode of transport for leaked or disposed waste in the Hanford Site geology is "along preferential, vertical, possibly tortuous pathways," where the total flow rates and volumes may exceed those expected in a broad plume. Some of the preferential pathways and associated concepts discussed by the panel included the following:

- Geothermal convection systems that might move contamination upward

- Dissolution of siliceous sediments by hot alkaline tank wastes

- Colloidal transport

- Preferential porous media pathways (i.e., short circuiting flow associated with structured or fractured soils, fingering flow, and funneled flow).

The panel hypothesized that funneled flow coupled with colloid transport, is the most likely mechanism to move large quantities of cesium-137 to depth. However, the panel also noted that vadose zone characterization has not adequately defined preferential pathways for use in predictive modeling. The panel further suggested that relevant concepts/tools from petroleum, geothermal, and other suitable sources be incorporated into transport models to simulate near-field tank phenomena.

C.2.2.5. Composite Analysis. The *Composite Analysis (CA) for Low-Level Waste (LLW) Disposal in the 200 Area Plateau of the Hanford Site* (Kincaid et al. 1998) was a radiological assessment to estimate doses to hypothetical future members of the public from radionuclides from LLW disposal and all other sources of radioactive contamination. This first iteration of the CA specifically addressed active or planned LLW disposal actions at the following locations:

- Post-1988 solid waste burial grounds in the 200 Areas
- The Environmental Restoration Disposal Facility (ERDF)
- Disposal facilities for immobilized low-activity wastes.

Kincaid et al. (1998) used stratified 1-D soil columns to represent the vadose zone beneath each facility. The stratigraphy selected for these soil columns was based on the major stratigraphic units defined by Thorne and Chamness (1992) and Thorn et al. (1993, 1994) encountered in the nearest of several selected coreholes throughout the 200 Areas. Each soil column contained three or four homogeneous and isotropic strata of constant thickness. The hydraulic characteristics assigned to each strata were based on the hydraulic parameters compiled by Khaleel and Freeman (1995a). The relationships between moisture content, pressure head, and unsaturated K was assumed nonhysteretic, and based on those by van Genuchten (1980) and Mualem (1976).

Initial moisture conditions were based on steady-state recharge simulations under natural recharge conditions. Infiltration from liquid disposal sites varied by disposal type. The infiltration rate from ponds was assumed equal to the infiltration rate allowed under unit gradient conditions, which was controlled by the K_{sat} of the least conductive geohydrologic unit. The wetted cross section of the 1-D column for cribs, trenches, french drains, etc., was set three times that defined by the K_{sat}, and the facility discharge rate. For tanks, the wetted cross section was assumed equal to the cross-sectional area of the tank bottom. Future recharge rates varied by the projected surface cover, based on projected end states.

Contaminant transport was controlled by linear sorption isotherms (K_d), which varied with depth and waste type. Two different K_ds were used for each of six waste types: a near field K_d that was affected by the high concentrations (e.g., high pH, high sodium) of the waste, and a far field K_d that was not affected.

C.2.2.6. Hanford Tanks Initiative AX and SX Tank Farm Screening Analyses. This study evaluated issues related to the vadose zone conceptual model and mechanisms that could decrease the travel time of contaminants through the vadose zone. This assessment used a 1-D stratified soil column with nine layers for the AX Tank Farm and five layers for the SX Tank Farm. Hydraulic characteristics were taken from Khaleel and Freeman (1995a). Recharge was assumed to range from 6.5 cm/yr (base case) to 0.1 and 13 cm/yr (sensitivity cases) after Fayer and Walters (1995). Future conditions assumed a *Resource Conservation and Recovery Act of 1976* (RCRA)-type surface cover and a recharge rate of 0.1 cm/yr (base case) and 0.05 to 0.5 cm/yr (sensitivity cases). Contaminant transport was assumed to be controlled by both near-field and far-field distribution coefficients (K_d) similar to that used in the CA.

Jacobs Engineering Group, Inc. (1998a, 1998b) confirmed that parameters that directly amplify the biosphere arrival rate (i.e., inventory, choice of K_d, and infiltration rate, or effects that enhance infiltration rates locally like the umbrella effect) would be expected to be the most important parameters because they most directly influence the rate of contaminant mass arrival. Jacobs Engineering Group, Inc. found that preferential pathways in the form of clastic dikes and borehole annular space did not have a major influence on the performance measure.

C.2.2.7. Hanford ILAW PA. The Immobilized Low-Activity Tank Waste (ILAW) Performance Assessment (PA) modeled potential releases to the environment from more than 200,000 m^3 of immobilized low-activity waste (i.e., a specially formulated glass waste form) to be produced during processing of waste currently contained in single- and double-walled tanks in 18 tank farms (Mann et al. 1998). The disposal is planned in two areas within the 200 East Area: existing underground vaults at the eastern edge and new, yet to be constructed vaults, at the southern edge.

A 2-D flow and transport model was used to simulate vadose zone flow and transport. For the base-case analysis, the stratigraphy was based on the major stratigraphic units defined by Reidel et al. (1995), and was comprised of the upper gravel, sand, and lower gravel sequences of the Hanford formation and Ringold Formation. All layers were assumed to be of uniform thickness and behave as homogeneous and isotropic media. For modeling purposes, no variation was considered in stratigraphy at the two disposal sites. Because no site-specific measurements were available, vadose zone hydraulic parameters were based on laboratory measurements of samples from the same strata found near the disposal sites. Van Genuchten (1980) and Mualem (1976) models were used to represent moisture retention and unsaturated conductivity relationships; unsaturated conductivities were estimated based on moisture retention and saturated conductivity measurements. Details on data used and parameter estimation methods are provided in Khaleel and Freeman (1995a).

Recharge estimates from meteoric infiltration were based on Rockhold et al. (1995) and provided for both estimated short-term and long-term recharge rates for ILAW disposal. The short-term

estimate (0.5 mm/yr) was based on the design specifications for the Hanford barrier, while the long-term estimate (3 mm/yr) was based on data presented in Fayer and Walters (1995). The vadose zone transport model considered both longitudinal and lateral dispersion processes. The longitudinal dispersivity was assumed to be $1/10^{th}$ of the travel distance within the vadose zone. The diffusion coefficient used in modeling was based on the Kemper and van Schaik (1966) diffusion model. A linear sorption isotherm (K_d) model was used; K_d values were used to differentiate among the non-sorbing (e.g., 0 for Tc), slightly sorbing (e.g., 0.6 for U), moderately sorbing (e.g., 3 for iodine [I]), and strongly sorbing (e.g., 100 for Cs) radionuclides. The K_d estimates were based on Kaplan et al. (1995a, 1995b). The K_ds were not varied over time and space. Sensitivity cases were performed to study effects of changes in K_d values, recharge estimates, stratigraphy and hydrologic parameter estimates, and dispersivity estimates. An external peer review identified a number of vadose zone field-scale processes (e.g., upscaling for hydraulic properties, macroscopic anisotropy, heterogeneous sorption-enhanced macrodispersivity) for consideration in the next iteration of ILAW PA (Mann et al. 1998).

C.2.2.8. Tank Waste Remediation System Environmental Impact Statement. The Tank Waste Remediation System Environmental Impact Statement (TWRS EIS) (DOE and Ecology 1996) used two 1-D soil columns to represent source areas in the 200 West Area and four in the 200 East Area. These geohydrologic models were based on information presented in the 200 East and 200 West Groundwater Aggregate Area Management Study Reports (DOE-RL 1993a, 1993c). These vadose zone models incorporated from one to four geohydrologic layers below tanks. Hydraulic properties were based on the grout performance assessment (200 East) and the 200 West LLW burial grounds performance assessment. Recharge was set at 50 mm/yr.

C.2.2.9. Retrieval Performance Evaluation. The Retrieval Performance Evaluation (RPE) (Jacobs Engineering Group, Inc. 1999) uses an updated version of the Caggiano (1996) conceptual model (Figure C-3). This updated conceptual model includes fingering and leaks down unsealed dry wells.

C.2.2.10. Solid Waste Burial Ground Performance Assessments. Burial grounds in the 200 West and East Areas were treated separately in PAs by Wood et al. (1995, 1996). The burial grounds receive solid waste (e.g., contaminated tools and clothing) from operations in the 200 Areas. In addition, some wastes are received from offsite generators within the DOE complex and the U.S. Department of Defense (e.g., U.S. Navy ship reactors in Trench 94 of 218-E-12B Burial Ground). Two types of disposal facilities were considered in Wood et al. (1995, 1996). The first facility (a Category 1 waste facility) is assumed to have no functional barriers and is intended to contain very low concentrations and quantities of radionuclides in the inventory. The second facility (a Category 3 waste facility) is assumed to have a cover that controls infiltration. Wood et al. (1995, 1996) used 2-D models to represent the vadose zone beneath each facility. For the 200 West Area burial grounds PA, the stratigraphy was based on Bjornstad (1990); the major stratigraphic units are the Hanford formation, Early Palouse, Plio-Pleistocene, and Ringold Formations. The stratigraphic units were assumed to be homogeneous and isotropic. For the 200 East Area burial grounds PA, the stratigraphy (i.e., upper gravel, sand and lower gravel sequences of the Hanford formation) was based on Lindsey et al. (1994). The hydraulic characteristics assigned to each strata were based on laboratory measurements of bulk density, saturated hydraulic conductivity, moisture retention, and unsaturated hydraulic conductivity for

Appendix C – Vadose Zone Conceptual Model

core samples from boreholes near the burial grounds. Details on laboratory measurements and parameter estimation are included in Wood et al. (1995, 1996). For gravelly soils, the laboratory-measured moisture retention data were corrected for the gravel fraction (Khaleel and Relyea 1997, Gardner 1986). Van Genuchten (1980) and Mualem (1976) models were used to represent moisture retention and unsaturated conductivity relationships.

A simultaneous fitting was performed using both moisture retention and unsaturated conductivity data; this fitting helps reduce uncertainty in estimated conductivities at low moisture contents typical of vadose zone soils beneath dry disposal sites (Khaleel et al. 1995).

A 2-D steady-state flow and transient transport model was used to simulate vadose zone flow and transport. Initial moisture conditions were based on steady-state recharge simulations under natural recharge conditions. Infiltration from the disposal sites was varied by facility type. Infiltration rates of 5 cm/yr and 0.5 cm/yr were assumed for Category 1 and 3 facilities, respectively. For transport calculations, longitudinal and lateral dispersivities of 1 and 0.1 m were assumed (Gelhar et al. 1992). A linear sorption isotherm (K_d) model was used to represent sorption. The K_ds were not varied over time and space. However, four K_d values were used to differentiate among the non-sorbing (e.g., carbon-14, iodine-129, technetium-99 and U), slightly sorbing, moderately sorbing, and strongly sorbing radionuclides (e.g., Am, Pu, Sn, Th) considered as part of waste inventory. Vadose zone flow and transport simulations were performed for a) advection-dominated; b) diffusion-dominated; and c) solubility-limited radionuclide release models from the burial grounds. A number of sensitivity cases were run to evaluate potential presence of clastic dikes below a disposal facility, variability in hydraulic properties, and recharge estimates.

C.2.2.11. ERC Studies of 200 Area Soil Sites. DOE-RL (1998c) presents a 200 Area scale discussion on generic contaminant/soil interactions, conceptual contaminant distribution models, and a high-level conceptual exposure model. DOE-RL (1997) presents preliminary conceptual models for each of the 23 soil operable units in the 200 Area. DOE-RL (1999a, 1999b) presents site-specific conceptual models for selected waste sites in the cooling water and chemical sewer operable units.

C.2.2.12. Tank Sluicing Studies. Two-dimensional flow and transport model sensitivity analyses were conducted to evaluate the impact of potential leaks due to hydraulic sluicing for the C-106 Tank (Lowe et al. 1993). A layered-cake stratigraphy (Stewart et al. 1987) was used as the basis for the vadose zone conceptual model; the layers were assumed to be homogeneous and isotropic. The van Genuchten (1980) and Mualem (1976) models were used to represent moisture retention and unsaturated conductivity relationships. Van Genuchten model parameters were primarily based on information from Smoot et al. (1989) for the nearby AX Tank Farm soils. For gravelly soils, the laboratory-measured moisture retention data were corrected for the gravel fraction (Khaleel and Relyea 1997 [includes more recent work], Gardner 1986). Gravel corrections for saturated hydraulic conductivity were made using the method of Bouwer and Rice (1984). For transport calculations, longitudinal and lateral dispersivities of 1 and 0.1 m were used (Gelhar et al. 1992). A linear sorption isotherm (K_d) model was used to represent sorption. Initial conditions at the start of sluicing were based on a) results of a steady-state simulation with an estimated 1 cm/yr recharge rate before the tank was built; and b) an estimated

10 cm/yr enhanced recharge resulting from the absence of vegetation and the presence of a gravel surface since the tank was built. Due to the "umbrella effect," the volume of water from recharge at 10 cm/yr over the area of the tank was assumed to runoff uniformly around the perimeter of the tank. Transport of leaked material to the water table was dependent on the enhanced recharge from the assumed umbrella effect. For example, the total volume of leakage for the base case is about 150 m^3 (40,000 gal), while recharge at 10 cm/yr (due to the umbrella effect) provides almost 400 m^3 (50,000 gal) of water, every year. Sensitivity of computed contaminant fluxes to the water table were evaluated for a) source area of leakage; b) assumed constant anisotropy of soils; c) barriers to infiltration of meteoric water; d) variations in recharge estimates; and e) presence of subsurface barriers. Based on numerical results, Lowe et al. (1993) concluded that small leaks are expected to find their way to groundwater. Simulated results suggest that providing an impermeable cover over the tank and the surrounding area could reduce adverse effects of enhanced recharge.

Piepho et al. (1996) conducted 2-D flow and transport model sensitivity analyses at the AX Tank Farm. A layered-cake stratigraphy was used as the basis for a "simplified" conceptual model, but "detailed" conceptual models were also considered that included thickening and thinning, pinchouts, and interfingering of various units of the Hanford formation at the AX Tank Farm. The stratigraphic units were assumed to be homogeneous and isotropic. Van Genuchten (1980) and Mualem (1976) models were used to represent moisture retention and unsaturated conductivity relationships. Van Genuchten model parameters were based on information from Khaleel and Freeman (1995a) and Kincaid et al. (1995) by matching available particle-size distribution data for AX Tank Farm soils to those for samples from other locations and from a similar lithologic unit. As in Lowe et al. (1993), the laboratory-measured, moisture-retention data and saturated hydraulic conductivity were corrected for the gravel fraction (Khaleel and Relyea 1997, Gardner 1986, Bouwer and Rice 1984). For transport calculations, longitudinal and lateral dispersivities of 1 and 0.1 m were assumed. A linear sorption isotherm (K_d) model was used to represent sorption. Initial conditions at the start of sluicing were based on a) results of a steady-state simulation with an estimated 1 cm/yr recharge rate before the tank farm was built; and b) an estimated 10 cm/yr enhanced recharge resulting from the absence of vegetation and the presence of a gravel surface since the tank farm was built. The sensitivity of computed contaminant fluxes to the water table were evaluated for a) variations in stratigraphy and hydraulic properties; b) volume, duration, and source area of leakage; c) simultaneous leakage from multiple tanks; d) pre-existing leaks; e) barriers to infiltration of meteoric water; and f) source contaminant concentrations and K_ds. Based on numerical results, Piepho et al. (1996) noted that the parameters that most affect the flux of contaminants to the water table were a) variations in stratigraphy and hydraulic properties; b) volume of leakage; and c) barriers to infiltration of meteoric water. The simulations indicated that, in the absence of an infiltration barrier within the first 30 years after sluicing, even a leak as small as 4,000 gal reached the water table.

C.2.2.13. Conceptual Model of Carbon Tetrachloride Contamination. Rohay (1999) presents an update of the conceptual model for the carbon tetrachloride site. Possible transport mechanisms and distributions of contaminant phases for the high concentration zone near the primary waste disposal sites are shown in Figure C-8. On a broad scale, the vadose zone was divided into three major units: 1) gravel and sand of the Hanford formation; 2) the fine-grained

Figure C-8. Schematic of Transport Mechanisms and Distributions of Carbon Tetrachloride Phases (Rohay 1999).
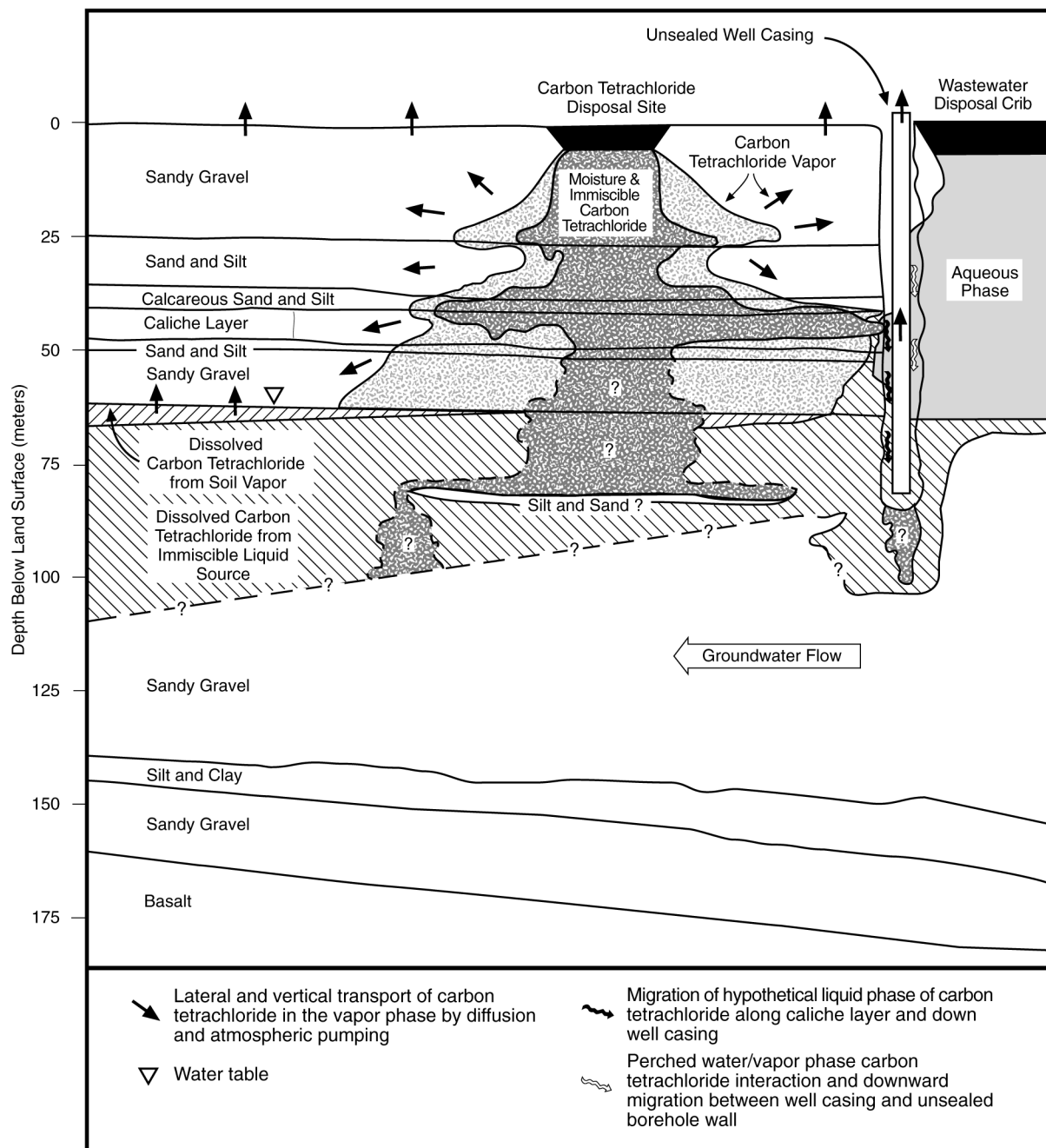
E9906104.4b

carbonate cemented Plio-Pleistocene unit (and overlying Early "Palouse" Soil); and 3) gravel and sand of the Ringold Formation. The Plio-Pleistocene unit is believed to have been an accumulation area for vapor, aqueous phase, and possibly residual dense non-aqueous phase liquid (DNAPL). Disposed liquid wastes would have been impeded by this unit during movement through the vadose zone. Other fine-grained zones in the Hanford formation and Ringold Formation may also be minor accumulation and spreading areas. Carbon tetrachloride may become irreversibly adsorbed within intra-particle sediment pore spaces in these fine-grained units. The sloping interfaces between hydrogeologic units, as well as the variability in thickness, cementation, and fractures, also provide hydrologic controls on the fluid movement.

Four separate phases of CCl_4 (i.e., vapor, dissolved aqueous phase, adsorbed phase, and a separate organic phase) may reside in the vadose zone. Soil vapor extraction (SVE) using a mix of extraction wells, changed periodically to improve its performance, has been effective at removing CCl_4 from the higher permeability zones. A total of 75,490 kg of CCl_4 (approximately 10% of the estimated release inventory) has been removed since remediation began in 1992. The Plio-Pleistocene unit appears to be the most significant continuing source of CCl_4 soil vapor. Pu and Am are distributed within the upper 30 m of the vadose zone and may have been carried downward by a combination of acidic waste liquids and organic complexant mixtures.

Rohay (1999) describes the various important transport processes within the vadose zone. These include vapor phase transport downward and laterally by molecular diffusion and by advective flow. Surface barriers (i.e., a building foundation or asphalt parking lot) could enhance the lateral extent of diffusion. CCl_4 vapor can also move by density-driven advection, or along pressure gradients caused by barometric pressure fluctuations. Atmospheric pressure fluctuations appear to present a significant release mechanism for CCl_4 vapor out of the vadose zone via the soil surface and through boreholes. DNAPL moves non-uniformly downward through the vadose zone and can be held by capillary forces as residual saturation in the soil pores. Boreholes are also potential pathways for preferential movement of CCl_4 vapor and liquid (both as dissolved and organic phases). Natural recharge and/or liquid effluent from nearby disposal facilities may dissolve and transport the CCl_4 vapor and/or residual liquid phases.

Transport through the capillary fringe must occur in the aqueous phase via diffusion, dispersion, advection, and fluctuation in the elevation of the water table. Lateral spreading also occurs at the capillary fringe until sufficient hydraulic head builds up to displace air and water to move into the groundwater. Residual DNAPL would remain at this interface even after the main body of contamination moved through the capillary fringe.

C.2.2.14. Hanford Site Consolidated Groundwater Project. The 1998 Annual Groundwater Report (Hartman 1999) summarizes the results of fiscal year 1998 groundwater and vadose zone monitoring and remediation activities on the Hanford Site. This report provides a comprehensive interpretation of current vadose zone and groundwater conditions on the Hanford Site, including a description of site hydrogeology, groundwater flow, and contaminant distribution.

Hartman (1999) found that radioactive and hazardous wastes in the soil column act as potential sources of continuing/future groundwater contamination. The continued infiltration of vadose-zone contamination to groundwater depends on contaminant chemistry, stratigraphy, and

drainage of water through the vadose zone. Even small leak sources can be mobilized if a driving force and/or a preferential vertical pathway is present to transport the contaminants through the vadose zone to groundwater. The role of ground-cover type, or enhanced natural infiltration, and preferential pathways is, thus, a crucial issue particularly in the tank farm areas.

The results of spectral gamma logging of 16 boreholes surrounding WMA B-BX-BY, suggest that gamma-emitting radionuclides may have been redistributed near 4 of these boreholes during the last 10 years. The evidence is questionable in some of those wells, and the significance of redistribution varies. Interpretation of the logging results from drywells in the BX Tank Farm supports the designation of Tanks BX-101, -102, -108, -110, and -111 as leakers, though in some cases mixing of leak plumes and leaks from pipelines complicates assignment of vadose-zone contamination with specific leaks (DOE 1998). Contamination at the bottom of some of the boreholes was interpreted to be an artifact of the casing (DOE 1998) (i.e., contaminated mud attached to the casing, particulate drag down, or water leakage down the interior or exterior walls of the casing).

- The 216-Z-1A, -9, and -12 Facilities were logged in FY 1998 to determine whether recent TRU movement had occurred beneath those facilities as a result, in part, of infiltration of natural precipitation. The surface of the 216-Z-1A tile field is approximately 2 m below the surrounding grade and is covered with gravel. Thus, infiltration at this facility is expected to be enhanced. Prompt fission neutron logging of boreholes at the 216-Z-1A tile field and one borehole at the 216-Z-12 Crib showed large activities of fissionable isotopes. Two of the boreholes at 216-Z-1A were logged with the prompt-fission neutron tool in 1978, and again in 1984. The distribution of contaminants (as seen from the 1993 log) agreed well with the previous logs, indicating that fissionable radionuclides, including plutonium, had not moved substantially during 15 years at the two boreholes. The general conclusion is that TRUs were relatively mobile at the time of discharge to the 216-Z-1A tile field, but have been fairly stable since. The mobility of TRUs (as organometallic complexes in the acidic waste streams discharged to the past-practice disposal facilities near the Plutonium Finishing Plant) were discussed in Section 4.4.5 of Hartman and Dresel (1998) and Johnson and Hodges (1997). The mechanism suggested by Johnson and Hodges might account for the distribution of high-activity TRUs to the 20- to 30-m depth in the 216-Z-1A tile field, as found in earlier soil-column characterizations (Price et al. 1979). It is also suggested that the TRUs could be adsorbed by the soil column after degradation of the organic complexing agents, resulting in stabilized contaminants. Alternatively, other soil-chemical reactions may have occurred (Price et al. 1979, Serne et al. 1996).

- The FY 1998 logging found that the subsurface distribution of Pu had changed around only one borehole (299-W18-179) at the 216-Z-12 Crib. The reason for the change is unknown. Although it is possible that Pu has been remobilized at the 5-m depth around the borehole, further investigation is needed to determine both the nature and the reasons for Pu remobilization.

- Comparing the distribution of TRUs beneath the 216-Z-1A and -12 Facilities shows a much deeper penetration of TRUs beneath the tile field. This comparison agrees with past characterizations at the two facilities (Price et al. 1979, Kasper 1982) and can be explained

by either the acidic disposal or the organometallic complexation process described by Johnson and Hodges (1997). Unlike the acidic, organics-containing waste stream disposed to the 216-Z-1A tile field, the waste stream sent to the 216-Z-12 Crib was neutral to basic and contained little organic-complexing agents. The initial mobility of TRU is expected to be greater in the former waste stream than in the latter. After the disposal occurred, both the acidic and organic complexes are expected to diminish via soil pH neutralization and biodegradation processes, and TRUs, especially Am and Pu, would be expected to adsorb strongly to the Hanford Site sediments. There has been no obvious Am or Pu migration deeper into the sediment profile at this disposal facility, but the protactinium-233 distribution may be interpreted as showing some migration of neptunium-237.

C.2.2.15. 100 Areas. The 100 Areas are the reactor areas along the Columbia River. Peak production years were reached in the 1960s, when nine production reactors were in operation. Occasionally during operations, the cladding around a fuel element would fail. This cladding failure would expose cooling water directly to the irradiated uranium fuel and its associated fission products. The cooling water, after a cladding failure, would be diverted from the retention basins to the ground through cribs and trenches, thereby allowing these fission products to adsorb to the soil in the vadose zone.

The cooling effluent removed from the N Reactor was discharged to the 1301-N and 1325-N Liquid Waste Disposal Facilities (LWDF). These facilities used the vadose zone to remove radioactive and hazardous materials from the reactor operation's effluent. As discharged effluent percolated through the soil column, most radioactive and chemical constituents were retained in the soil column through filtration, adsorption, and ion exchange. However, some constituents, (i.e., tritium) were not retained in the soil and traveled with the effluent. Eventually the soil's capacity to remove contaminants from the effluent was exceeded, allowing some constituents (e.g., strontium-90) to travel to groundwater and the Columbia River.

The liquid effluent from the reactors was low-ionic strength solutions with low to high activity. Because of the large volumes of fluids discharged, the vadose zone may contain from tens to thousands of curies of radioactivity (Dorian and Richards 1978, DOE/RL 1998). The large volumes of water discharged to the vadose zone caused mounding in the unconfined aquifer under these facilities. These water table mounds were 6 to 9 m higher than the natural water table. The difference between artificial recharge and natural recharge (present day conditions) is large. For example, for the 1301-N LWDF, the area was calculated and compared to the volume of water discharged into the facility over the course of a day. The 7,000 L/min discharge is equivalent to a recharge rate of approximately 2 m/day of rainfall, or one year of operation would be equal to 7,000 years of natural recharge.

In addition to the releases to the vadose zone by the retention basins and liquid waste disposal facilities, there are unplanned releases by breaks in effluent pipelines, stock solution spills of sodium dichromate in the 100-D Area (Carpenter 1993), and diesel fuel leaks in the 100-N Area (WHC 1994).

The vadose zone in the reactor areas is not well characterized. However, Dorian and Richards (1978) found that soil contamination dropped to background levels within 1.5 to 6.1 m below the

bottoms of most of the cribs, trenches, or retention basins. Additionally, Peterson et al. (1996) provided moisture content and unscaled saturated hydraulic conductivities for vadose zone sediments in these areas. They reported that Hanford formation gravels in the vadose zone typically had 1.5 to 10 weight percent (wt %) moisture content with a wide variance in reported saturated hydraulic conductivities.

Hope and Peterson (1996) found hexavalent chromium in pore-water samples taken from the Columbia River bottom and in aquifer sampling tubes placed along the riverbank in the 100-D Area. Because of the high levels of chromium found in these samples, a sampling program (Connelly 1998a, 1998b) was established to determine the source of chromium. This sampling program found chromium concentrations in the groundwater at levels well above those of the dilute cooling water solutions used to inhibit corrosion (equivalent to 700 µg/L of Cr[VI]), but neither delineated the extent of the plume nor discovered the source area for the plume. Additional 1999 sampling has not found Cr(VI) in the vadose zone.

The vadose zone at the 100-N Area has been well characterized due to the liquid-effluent disposal practices at the 1301-N and 1325-N LWDF and the presence of strontium-90 in the groundwater along the Columbia River. These characterization studies collected data from the vadose zone on the following:

- Geochemistry (Crews and Tillson 1969; Robertson et al. 1982, 1983; Fruchter et al. 1984, 1985; Serne and LeGore, 1996, Knepp 1995)

- Contaminant distribution within the vadose zone (Robertson et al. 1982, 1983; Fruchter et al. 1984, 1985; DOE 1996a; Knepp 1995)

- Physical properties (Connelly et al. 1991, DOE-RL 1996a)

- Moisture retention properties (Connelly et al. 1991, DOE-RL 1996a)

- Geophysical measurements (DOE-RL 1996a)

- Moisture content (DOE-RL 1996a)

- Impacts to the vadose zone by the Columbia River (DOE-RL 1996b).

For their limited field investigation of the LWDFs, DOE-RL (1996a) drilled and sampled the vadose directly underneath and just to the side of the 1301-N and 1325-N LWDF. Before this field investigation was conducted, an estimate for the thickness of the contaminated zone for strontium-90, cesium-137, cobalt-60, and plutonium-239/240 (using the concentration at the bottom of the facility) was made. The results of this estimate for strontium-90 and cesium-137 were used to estimate the contaminant concentrations in the soil before drilling. Sampling confirmed the mass balance calculations (Figure C-9). Although at well N-103, cesium-137 was found at levels slightly above the detection limits. No other samples between the 1301-N LWDF and this well had cesium-137 at levels above detection. This may represent movement of cesium-137 by colloids.

Figure C-9. Results of Vadose Zone Sampling for Strontium-90 and Cesium-137 at the 100-N Area.
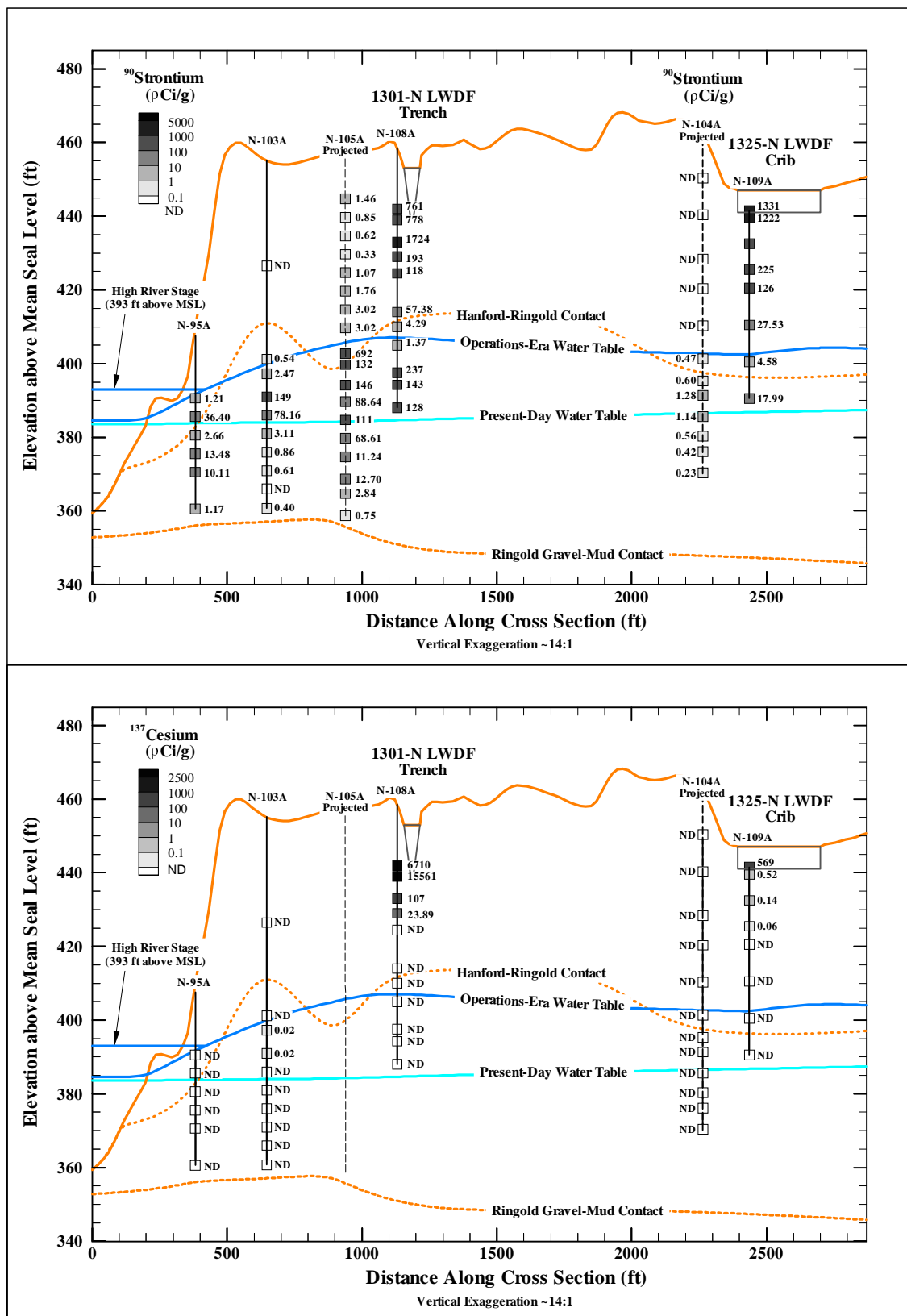
DOE-RL (1996a) found that the volumetric moisture content in wells 199-N-107A, 199-N-108A, and 199-N-109A varied from 10 to 20%, while the expected moisture content for these sediments would be between 5 to 8%. The higher moisture content in these wells indicates the sediments underneath these facilities are still draining.

The 100 N Area has also had unplanned petroleum releases during operations. The largest release occurred in 1996 when external corrosion of a diesel supply line released approximately 303,000 L of Number 2 diesel fuel to the soil. The diesel fuel migrated through the soil into the groundwater, and, subsequently, into the Columbia River. Much of the diesel was collected in an interceptor trench excavated parallel to the river. However, diesel fuel is still found above the aquifer, and the amount of diesel fuel remaining in the vadose zone is unknown.

Results from the geochemistry characterization studies show a contaminant zoning effect in the vadose zone. Contaminants, like tritium, that show little to no adsorption, moved rapidly through the vadose zone to the groundwater and out to the Columbia River during operations. Crews and Tillson (1969), using I-131 isotopic analysis, estimated the travel time to the Columbia River from 1301-N LWDF to be approximately 10 days. Contaminants that show moderate adsorption (i.e., strontium-90) show distinctive zoning within the vadose zone. Serne and LeGore (1996), examining characterization data from 12 boreholes within the 100-N Area, found that strontium-90 in the vadose zone is bound to sediments directly underneath the LWDFs and in a relatively thin layer at depths that correspond to the elevated water formed during operations. Serne and LeGore (1996) also reported the bulk distribution coefficient (K_d) for strontium-90 to be 15 ml/g for these sediments. Contaminants with strong adsorption (i.e., cobalt-60, cesium-137, and plutonium-239/240) remained within 1 m of the bottom of the disposal facility. A conceptualization of the contaminant distribution and zoning is given in Figure C-10.

The Columbia River (along the Hanford Reach) is a hydrologic boundary that affects the groundwater and vadose zone along the 100 Areas. Flow volume is controlled upstream by the Priest Rapids and can result in daily river stage fluctuations of up to 2.4 m. These daily fluctuations can influence hydraulic gradients and groundwater levels as much as 150 m inland of the Columbia River. Seasonal fluctuations in the river stage can influence hydraulic gradients and groundwater levels up to 500 to 600 m inland.

The large leakage and discharges to the vadose zone during operations caused mounding in the unconfined aquifer. Although the unconfined aquifer has returned to non-mounded conditions, contaminants associated with the leakage and disposal practices are located in the vadose zone within the old water table mound. This can be seen in the upper plot of Figure C-7. Away from the LWDFs, the upper vadose zone is characterized with non-detectable concentrations of strontium-90 until the old water table mound is encountered at that point strontium-90 levels in the vadose zone sediments rise. When the Columbia River levels rise during the spring and early summer runoff, the unconfined aquifer rises into vadose zone sediments containing higher concentrations of contaminants resulting in higher contaminant levels in the groundwater (Figure C-11). This fluctuating water may remobilize contamination held within the intermittently saturated sediments immediately above the water table.

Figure C-10. Conceptualization of Radionuclide Distribution Beneath 1301-N and 1325 N.

Cross Section of Contamination From Liquid Waste Disposal Facilities (LWDFs)

Z-Exaggeration = 10

Placement of ^{90}Sr

~2997 Ci of ^{90}Sr Released to 1301 & 1325 LWDFs
~1126 Ci haved decayed away by January 1, 1996
~46.1 Curies to the Columbia River from 1972-1993
~88 Curies in the Unconfined Aquifer (0.8 dissolved in groundwater & 87 absorbed on sediments)
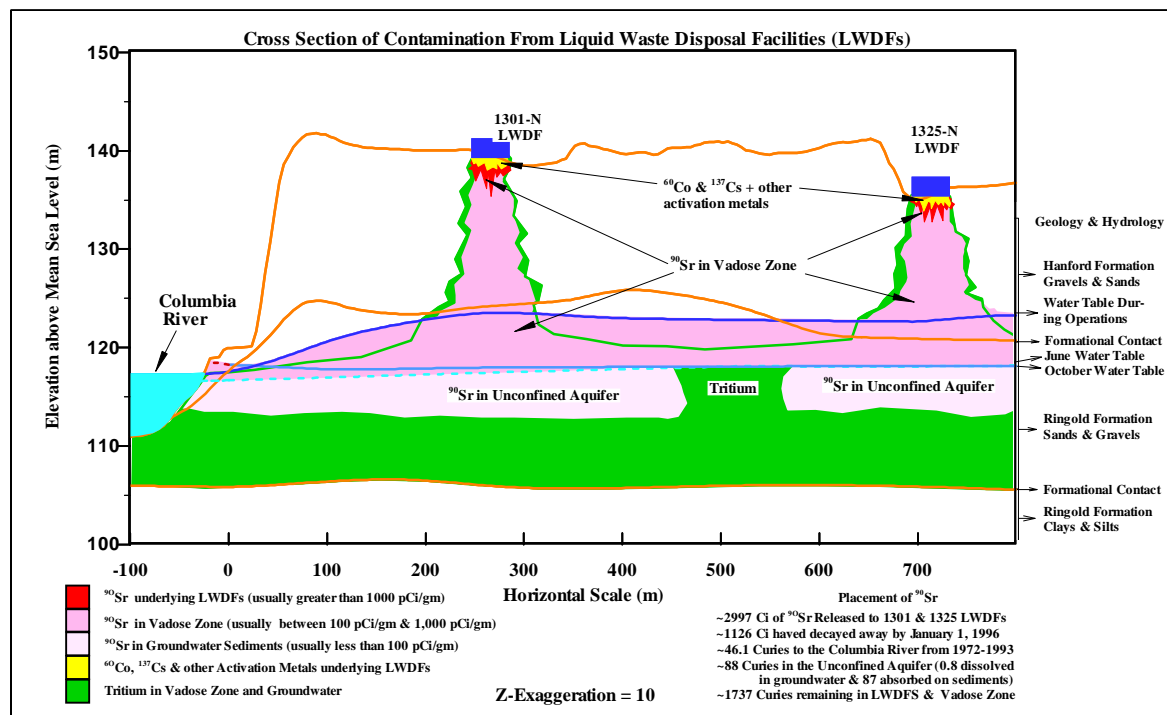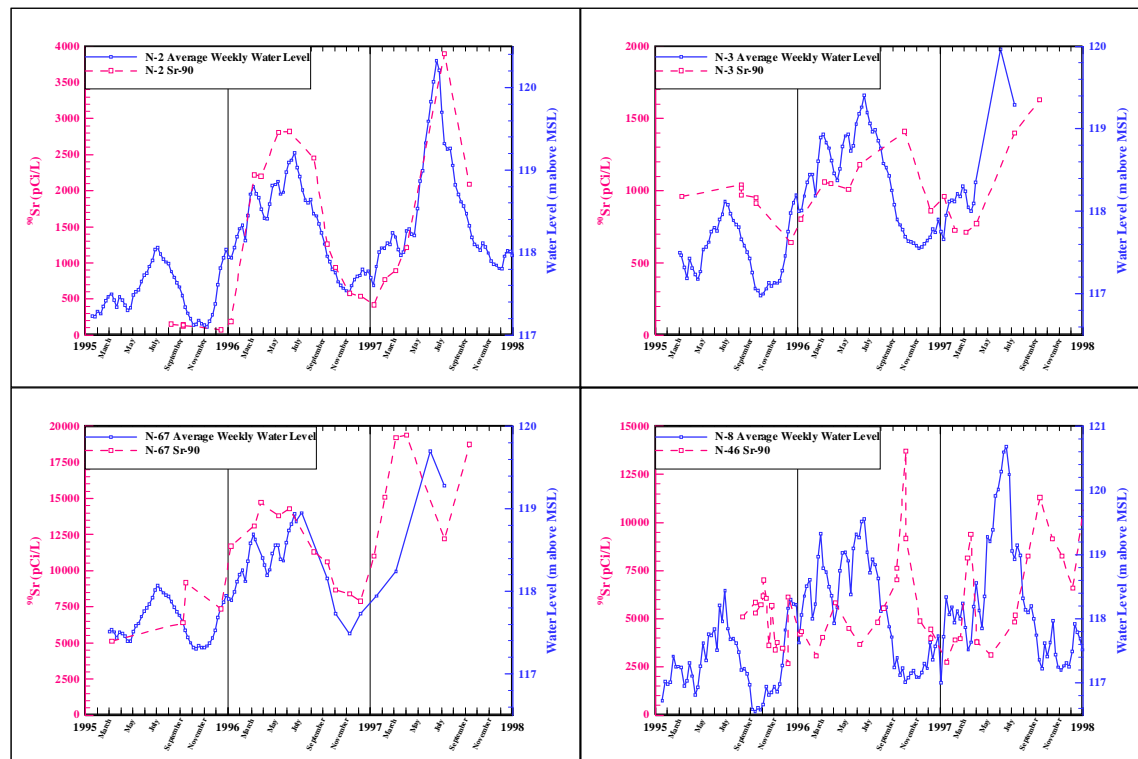~1737 Curies remaining in LWDFS & Vadose Zone

Figure C-11. Comparison Between Water-Levels and Strontium-90 Concentrations at Selected 100-N Area Wells.

Appendix C – Vadose Zone Conceptual Model

Two modeling studies examined the release from the 100-N Area source facilities to the Columbia River. Lu (1990) used a 2-D cross-sectional model, while Connelly et al. (1991) used a 3-D model. Both studies examined the historical release for strontium-90 from these facilities. They found, using a K_d of 15 ml/gm, the models overestimated strontium-90 release to the river from these facilities. To match the model results to field results, a thin, strongly adsorbing layer for strontium-90 was placed at the bottom of the disposal facilities.

DOE-RL (1996a) estimated the travel time to a nominal water table located at 117.35 to 118.35 m above mean sea level (MSL) from three vadose zone locations above the water table. These locations included 1) an elevation of 119.8 m above MSL, representing a seasonal high water table; 2) an elevation of 125 m above MSL, representing the top of the old water table mound; and 3) the bottom of the 1301-N and 1325-N LWDF. Table C-1 provides these travel time calculations for water or a non-sorbed species, a moderately adsorbed species (strontium-90) and highly adsorbed species (cesium-137). For these travel time calculations, DOE used a 1-D unit gradient model and the physical properties collected during the limited field investigation. The physical properties were from distinct soil zones found in the limited field-investigation boreholes. These distinct soil zones were based on the particle size distribution.

Table C-1. Travel Time Calculations for the 100-N Area.

Recharge Rate cm/yr	Travel Time in Years to the 1995 Water Table (117.35 to 118.35 m above Mean Sea Level)								
	1996 High Water Table 119.8 m above MSL			Old Groundwater Mound 125 m above MSL			Bottom of 1301-N		Bottom of 1325-N
	199-N-107A	199-N-108A	199-N-109A	199-N-107A	199-N-108A	199-N-109A	199-N-107A	199-N-108A	199-N-109A
Water									
15	1.9	1.8	1.6	7	10	4.2	21.2	19	8.6
8	3.2	3	1.9	11.6	17	7.2	35.6	32	14.9
2	10.2	9.9	7.2	38	57.3	26.3	119	108	53
Sr-90									
15	480	520	341	1,485	1,495	1,400	3,910	3,270	3,400
8	865	940	620	2,690	2,700	2,535	7,080	5,920	6,160
2	3,580	3,880	2,650	11,100	11,200	10,600	29,300	24,500	25,600
Cs-137									
15	1,590	1,720	1,130	4,940	4,960	4,660	13,000	10,900	11,300
8	2,880	3,120	2,060	8,450	8,980	8,540	23,500	19,700	20,500
2	11,900	12,900	8,830	37,000	37,150	35,200	97,300	81,400	85,200

C.3 CONCEPTUAL MODELS FOR SAC (REV. 0)

The SAC is being developed to assess the cumulative impacts of radioactive and chemical wastes at the Hanford Site. The purpose of the initial SAC (Rev. 0) is to demonstrate that an assessment of the scale and scope of the Hanford Site and the Columbia River can be conducted. This initial demonstration is posed as either a post-closure or a no action analysis of human, ecological health, and cultural and socioeconomic impacts. The large scale and complexity of this assessment, together with the lack of detailed characterization data and/or understanding of some of the detailed fate and transport processes, will necessitate simplification (and in some cases –

perhaps over simplification) of the site features, the release events, and the contaminant fate and transport processes. Thus, the use of sensitivity and uncertainty analyses will be important to capture the effects of this simplification.

The following sections present some of the important conceptual model concepts for the vadose zone, and present some options (i.e., study sets) for representing these concepts in the initial SAC (Rev. 0).

C.3.1 Features

This section discusses the physical structure (e.g., geology, hydrologic properties, geochemical properties) of the vadose zone and its principal transport pathways. Other features of the vadose zone conceptual model (e.g., climate and weather statistics, terrestrial ecology, and projected land use) are not specifically discussed. Some aspects of the climate and weather phenomena are discussed as they relate to precipitation, runoff, and infiltration. The reader is referred to (Neitzel 1999) for general discussions on these specific features.

The following discussion is comprised of three general physiographic areas (the 100, 200, and 300 Areas) that contain the majority of the waste disposal facilities, principally those with liquid waste disposal sites and tanks, have the potential for leaks or leaching, and/or have experienced past leaks and spills. Note that while other selected areas away from these focus areas (i.e., areas representative of background conditions and areas that have the potential to become contaminated in the future) are also important to the general vadose zone technical element, they are not specifically addressed in the conceptual model for SAC (Rev. 0).

C.3.1.1. 100 Areas. The present-day thickness of the vadose zone in the reactor areas ranges from 6 m (100-F Area) to more than 30 m (100-B/C Area), with each reactor area being slightly different. During operations, the groundwater mounding reduced the thickness of the vadose zone by 6 to 9 m directly under the retention basins or the liquid-waste disposal facilities.

C.3.1.1.1. Hydrostratigraphy. The vadose zone can be divided into two hydrostratigraphic units: the coarse-grained sequence of the Hanford formation, and the gravels of Ringold Unit E (Peterson et al. 1996; Hartman and Lindsey 1993; Lindberg 1993a, 1993b; Lindsey and Jaeger 1993). Unit E of the Ringold Formation comprises the lower portion of the vadose zone at the 100-K, 100-N, and 100-D Areas. It is only partially present in the 100-B/C Area and not present in the 100-H and 100-F Areas. Unit E is a fluvially deposited pebble-conglomerate exhibiting a sandy matrix. Unit E can be well-cemented to uncemented; cemented horizons are often laterally extensive, but somewhat discontinuous.

The uppermost geologic unit of significance within the 100 Areas is the coarse-grained sequence of the Hanford formation. The Hanford formation commonly has an open framework texture composed of uncemented, clast-supported pebble, cobble, and boulder gravel with a coarse-grained sandy matrix and minor sand and silt interbeds. The clast size decreases in the lower portion of the Hanford formation. The Hanford formation extends from the surface to just above the water table when Ringold Unit E is present. Otherwise, the Hanford formation extends and comprises the unconfined aquifer in the 100-H and 100-F Areas.

Although clastic dikes have been observed in the vadose zone beneath the 100 Areas (Fecht et al. 1999), they are not considered to represent significant preferential pathways. However, the contact between Ringold Unit E and the Hanford formation is important because the saturated hydraulic conductivity for the coarse-grained sequence of the Hanford formation is one to two orders of magnitude higher than the denser and locally cemented Ringold Unit E. Because hydraulic conductivity varies with the formation, different groundwater level responses could occur where channels now filled with the Hanford formation had been scoured into the Ringold Unit E. These channels could become preferential pathways for contaminated groundwater during high river stages.

C.3.1.1.2. Hydraulic Properties. The physical properties of the vadose zone in the 100 Areas are not well characterized. Peterson et al. (1996) gives saturated hydraulic conductivity, moisture content, specific gravity, and bulk density for samples taken from the single-pass reactor areas. No scaling of hydraulic conductivity (based on particle size distribution) was performed for that report. Khaleel and Relyea (1997) published moisture retention data for the 100-D, 100-F, and 100-H Areas. In the 100-N Area, Connelly et al. (1991) collected 10 surface samples for moisture retention data, and DOE-RL (1996a) collected four samples each from Boreholes 199-N-108A and 199-N-109A. The measured physical properties for these samples vary widely reflecting the heterogeneity of the vadose zone. Khaleel and Freeman (1995b) provide the best available information on the variability of vadose zone flow parameters (based on 200 Area samples; refer to Section C.3.1.2.2).

C.3.1.1.3. 100 Areas Conceptual Model. Vadose zone contamination in the 100 Areas is primarily the result of waste effluent to liquid waste disposal facilities and leakage from the retention basins and, to a lesser extent, by accidental releases of contaminants through low-volume leaks and spills, and dry waste burial grounds. Billions of liters of cooling water and wastewater have infiltrated through the vadose, creating large contamination plumes within the vadose zone. This water contained mostly radionuclides and inorganic metals.

Results from the geochemical characterization studies show a contaminant zoning effect in the vadose zone. For radionuclides and inorganic contaminants that are not adsorbed (i.e., tritium, nitrate, etc.), the large releases of water to the vadose zone at the retention basin and LWDFs quickly pushed these contaminants through the vadose zone and into the unconfined aquifer, and subsequently out to the Columbia River. Crews and Tillson (1969), using I-131 isotopic analysis, estimated the travel time to the Columbia River from 1301-N LWDF to be approximately 10 days. However, it is uncertain if all of the contaminated water has drained from the vadose zone, and these contaminates could still be leaching into the unconfined aquifer from the vadose zone.

Volumetric moisture content found in sediments under the 100-N Area LWDFs (DOE-RL 1996a) appear to be high for the given sediment type and natural recharge rate. This suggests these soils are still draining.

Contaminants that show moderate adsorption (i.e., strontium-90) show distinctive zoning within the vadose zone. Serne and LeGore (1996), examining characterization data from 12 boreholes within the 100-N Area, found that strontium-90 in the vadose zone is bound to sediments directly

underneath the LWDFs and in a relatively thin layer at depths that correspond to the elevated water table formed during operations. Serne and LeGore (1996) also reported the bulk K_d for strontium-90 to be 15 ml/gm for these sediments. Contaminants with strong adsorption (cobalt-60, cesium-137, and plutonium-239/240) remained within 1 m of the bottom of the disposal facility. A conceptualization of the contaminant distribution and zoning is given in Figure C-10.

C.3.1.1.4. Important Features of the 100 Areas Vadose Zone Model. The large volumes of discharge during operations created water table mounds 6 to 9 m above the nominal water table under the retention basins and disposal facilities. The sediments located within the operational water table became contaminated with radionuclides and inorganic metals because of the discharge operations. These sediments are now part of the vadose and should be considered a source term for further downward migration to the water table. Although clastic dikes are not considered significant preferential flow paths in the 100 Areas, significant preferential flow could occur along contacts between the Hanford formation gravels and the Ringold Formation (particularly where finer grained facies are found near the top of the Ringold). The hydraulic conductivity of the Hanford formation gravels is 10 to 100 times greater than Ringold Unit E. This contact is an erosional unconformity; therefore, channels of Hanford formation gravels could exist within the Ringold Formation providing preferential pathways.

Further complicating the release of contaminants from the vadose zone in the 100 Areas is the seasonal and diurnal fluctuations of the Columbia River. A high river stage causes the water table to rise into sediments containing higher concentrations of contaminants. Additionally, the chemistry changes caused by the constant re-wetting of the soil (due to diurnal fluctuations) could affect how the contaminates are released from the vadose zone.

C.3.1.1.5. Options for Vadose-Zone Transport Model in the 100 Areas. A representative flow and transport model of the vadose zone within the 100 Area (ignoring long-term geomorphic and climatological changes) should consider the following:

- At least two hydrostratigraphic units: the Hanford formation gravels and Ringold Unit E, and their site-specific ranges in physical and chemical properties (based on available geologic, soil physics, and geochemical data from nearby boreholes and outcrops)

- Location and geometry of the Hanford formation gravels - Ringold Unit E contact

- Continued downward migration of contaminants from source areas and from contaminated vadose zone sediments

- Seasonal high water flows on the Columbia River that will raise the water table into sediments containing higher concentrations of contaminants. When the seasonal high water drains from the aquifer, additional contaminants at higher concentrations could be released

- Diurnal fluctuations could impact how contaminants are released from the vadose zone to the aquifer

- Contamination zoning within the old water table mounds.

C.3.1.2. 200 Areas. A geologic cross section showing the general stratigraphy through the 200 Areas is shown in Figure C-12.

Figure C-12. Generalized West-to-East Geologic Cross Section Through the Hanford Site.
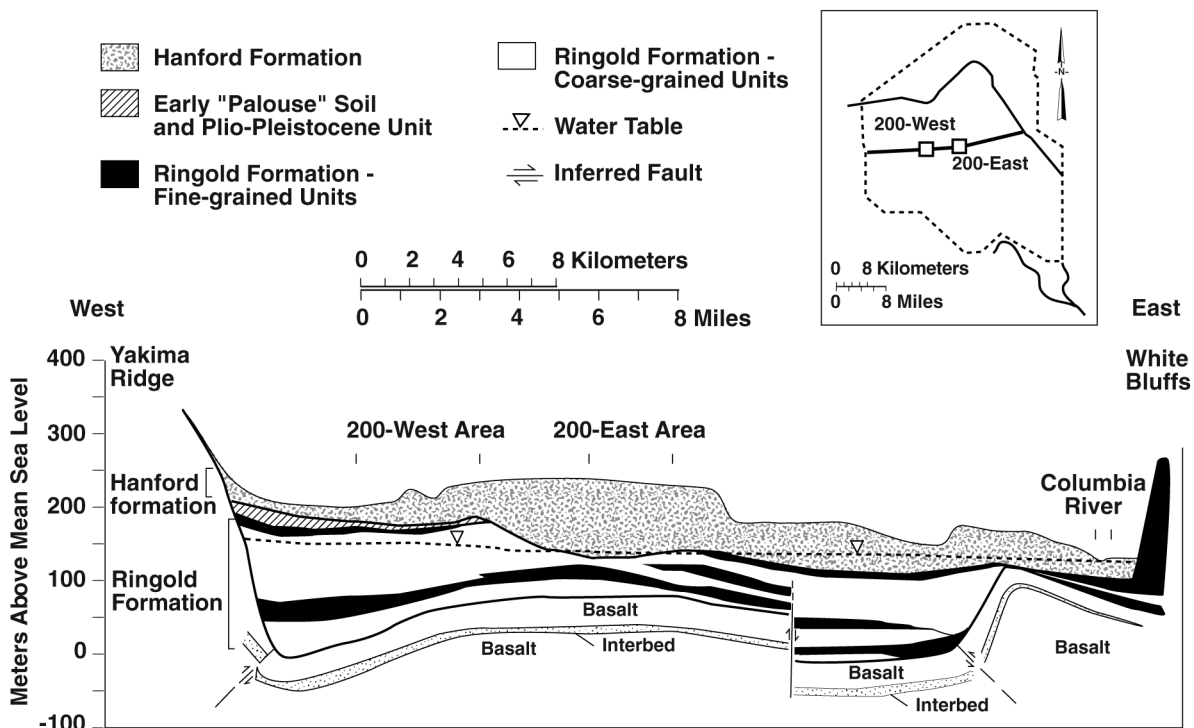
C.3.1.2.1. Hydrostratigraphy. The 200 Areas (200 East Area and 200 West Area) are located on the central plateau of the Hanford Site. The geology and hydrology of these areas have been extensively studied because they contain major sources of groundwater contamination (Hartman 1999). Geologic units that comprise the vadose zone in the 200 East Area include the glaciofluvial Hanford formation and the Ringold Formation. Within the 200 West Area are two additional units: the early "Palouse" soil and the directly underlying Plio-Pleistocene unit.

200 West Area. The vadose zone in the 200 West Area ranges from 50 to 80 m thick and can be subdivided into six principal hydrostratigraphic units (Lindsey et al. 1992a, Connelly et al. 1992a, and Thorne et al. 1993) (Table C-2). These units include two facies of the Pleistocene Hanford formation (the coarse-grained facies and fine-grained facies), Early Palouse Soil, Plio-Pleistocene (caliche), Upper Ringold, and Ringold Gravel (Unit E). These units are not present everywhere within the 200 West Area, and as in any depositional system, the thickness, distribution, and continuity of these units can vary significantly from site to site.

Table C-2. Comparison of Nomenclature Used for Vadose-Zone Hydrostratigraphic Units Within the 200 West Area.

Hydrostratigraphic Unit Used for This Study	Equivalent Designation in Lindsey et al. (1992a) and Connelly et al. (1992a)	Equivalent Designation in Thorne et al. (1993)	Equivalent Designation in Kincaid et al. (1998)
Hanford formation (Coarse)	Hanford formation coarse-grained facies	Unit 1	None
Hanford formation (Fine)	Hanford formation fine-grained facies		West Hanford Sand
Early Palouse Soil	Early Palouse Soil	Unit 2	West Early Palouse
Plio-Pleistocene (caliche)	Plio-Pleistocene unit	Unit 3	Plio-Pleistocene
Upper Ringold	Upper Ringold Formation	Unit 4	West Ringold
Ringold Gravel Unit E	Ringold Unsaturated Gravel Unit E	Unit 5	

Clastic dikes occur as near vertical, sediment-filled structures that cut across bedding planes of the Hanford formation. Clastic dikes have been observed to form polygons, based on observations of the ERDF excavation (Fecht and Weekes 1996). A multisided polygonal cell encloses the host sediments. Individual polygonal cells are bounded by other polygons to form what is described as a honeycomb pattern when viewed from the air (Fecht et al. 1999). Vertically oriented clay skins within clastic dikes could locally act to form an impediment to lateral flow atop fine-grained strata.

Perhaps the most significant feature in the 200 West Area affecting vadose-zone transport is the fine-grained and carbonate-cemented Plio-Pleistocene unit (Rohay et al. 1994), which represents an ancient buried calcic paleosol sequence (Slate 1996). Because of the cemented nature, the Plio-Pleistocene unit is often considered impervious, but it is also structurally brittle and, therefore, may contain many fractures that have developed since soil development. The degree of cementation varies considerably within the Plio-Pleistocene unit so that contaminants could breach the unit through discontinuities in cementation or structure. The Plio-Pleistocene unit may also chemically react with transported wastes with which it comes in contact. Immediately overlying the Plio-Pleistocene unit is the early Palouse soil unit, a loose fine-grained material, which has a relatively high moisture-retention capacity and would tend to retard the downward movement of moisture and contaminants until such time it reached saturation.

200 East Area. The vadose zone beneath the 200 East Area can be subdivided into five principal hydrostratigraphic units, including three Hanford formation units and two units belonging to the Ringold Formation (Lindsey et al. 1992b, Connelly et al. 1992b, Thorne et al. 1993). The Hanford formation units include 1) an upper Hanford formation gravel; 2) Hanford formation sand; and 3) a lower Hanford formation gravel (Table C-3). Over most of the 200 East Area, the Hanford sand facies lie between the upper and lower sequence of the Hanford gravel facies (Lindsey et al 1992b, Connelly et al. 1992b). Based on borehole samples, the upper and lower gravel sequences have similar physical and chemical properties. The Ringold Formation in the 200 East Area is, for the most part, eroded away in the northern half of 200 East Area. Here, the

Appendix C – Vadose Zone Conceptual Model

Table C-3. Comparison of Nomenclature Used for Vadose Zone Hydrostratigraphic Units Within the 200-East Area.

Hydrostratigraphic Unit Used for This Study	Equivalent Designation in Lindsey et al. (1992b) and Connelly et al. (1992b)	Equivalent Designation in Thorne et al. (1993)	Equivalent Designation in Kincaid et al. (1998)
Hanford formation Gravel (upper)	Hanford formation upper gravel sequence	Unit 1	East Hanford Gravel
Hanford formation Sand	Hanford formation sandy sequence		East Hanford Sand
Hanford formation Gravel (lower)	Hanford formation lower gravel sequence		East Hanford Gravel
Ringold Gravel	Ringold Unit A, Unit E	Units 5, 7, 9	East Ringold
Ringold Lower Mud	Ringold Lower Mud Sequence	Unit 8	

Hanford formation lies directly on top of basalt bedrock. The water table lies within the Ringold Formation just south of 200 East Area. Because the physical and chemical characteristics of the Ringold Unit A and Ringold Unit E gravels are similar, and because only a small portion of the vadose zone lies within the Ringold Unit A gravel, these units can be combined into a single hydrostratigraphic unit, namely the Ringold gravel unit.

In recent years, as the water table has declined in elevation, the basalt bedrock has become unsaturated beneath the northeastern portion of 200 East Area.

Clastic dikes have also been observed in the Hanford formation beneath 200 East Area. The vertically oriented clay skins within clastic dikes could locally act to form an impediment to lateral flow atop fine-grained strata. This impediment could then cause ponding (perching) of the water and eventual breakthrough to underlying strata.

Sublinear to anastamosing channel cut scour and fill features within the Hanford formation that could act as preferential pathways in the horizontal direction. Other types of heterogeneity are associated with stratigraphic pinch out or offlapping/onlapping of facies.

The Ringold Formation and the Hanford formation often contain relatively thin fine-grained stringers that can result in lateral spreading of moisture and slow down the vertical movement of contaminants within the vadose zone. Low-permeability layers, where they exist, often occur as single, relatively thick (meters or more) and continuous layers within the Ringold Formation. Low-permeability layers within the Hanford formation occur more frequently, yet are relatively thin (0.5 m or less) and laterally discontinuous. Low-permeability layers within the Hanford formation Sand unit are generally thicker and more continuous than those in the Hanford formation Gravel unit. Paleosols and some facies changes (i.e., the contact between fine grained and overlying coarser grained facies) have been observed to be fairly continuous over the range of at least 100 m and have been found to promote lateral spreading of crib effluent on that same scale.

C.3.1.2.2. Hydraulic Characteristics. Accurate predictions of flow and transport in the vadose zone require a detailed characterization of the hydrologic properties and their variability, and estimates of transport parameters such as dispersivity. In particular, data that are essential in quantifying the water storage and flow properties of unsaturated soils include the soil moisture characteristics (i.e., soil moisture content versus pressure head and unsaturated hydraulic conductivity versus pressure head relationships) for sediments in various geologic units.

Data on particle-size distribution, moisture retention, and saturated hydraulic conductivity (K_s) are cataloged for 183 samples from 12 locations in 200 East and West Areas (Khaleel and Freeman 1995a). The moisture retention data and K_{sat} values are corrected for gravel content. After the data are corrected and cataloged, hydraulic parameters are determined by fitting the van Genuchten soil-moisture retention model to the data. Khaleel and Freeman (1995a) provide summary tables of the van Genuchten parameters (i.e., α, n, θ_r, θ_s) and K_s data for all available samples by soil type and formation (Table C-4).

Based on Khaleel and Freeman (1995a), vadose zone hydraulic parameters were established for the composite analysis (Kincaid et al. 1998) for each formation defined in the preceding section. These parameters are provided in Table C-5. A normal distribution was assumed for the van Genuchten-fitted parameters n, θ_r, and θ_s. A log-normal distribution was assumed for the fitted parameter α and the laboratory-measured K_s.

Macrodispersivity Estimates For Non-Reactive Species. The Gelhar and Axness (1983) equation can be used to estimate asymptotic values of macrodispersivity.

$$A_L(<\psi>) = \sigma_{LnK}^2 \lambda \quad (1)$$

where:

longitudinal macrodispersivity depends on the mean pressure head $<\psi>$
λ is vertical correlation scale (i.e., average distance over which conductivities are correlated) for log unsaturated hydraulic conductivity
and
σ_{LnK}^2 is variance of log unsaturated conductivity.

To apply equation (1), an estimate of the vertical correlation scale for unsaturated conductivity is needed. For saturated conductivity, a correlation length of the order of about 100 cm was obtained for the sand-dominated sequence of Hanford formation in the 200 East Area (Khaleel 1999). However, compared to the saturated K's, an increase in the variance of log conductivity is expected to be compensated, in part, by a decrease in the correlation scale of log unsaturated conductivity. A correlation length of 30 cm is assumed for the unsaturated K. Unsaturated conductivities are based on laboratory measurements of samples from a borehole at the ILAW site. For σ_{LnK}^2 of 3.1 (i.e., log unsaturated conductivity variance at a recharge rate of about 0.1 cm/yr), equation (1) provides a longitudinal macrodispersivity of about 100 cm (Table C-6)

Table C-4. Summary of Hydrologic Properties (Khaleel and Freeman [1995a])

	Eolian Sand	Hanford Gravel	Hanford Sand	Ringold (Undifferentiated)
Inverse Air-Entry Pressure (α) in L/cm				
Minimum	2.11E-02	2.60E-03	5.90E-03	6.20E-03
Maximum	3.87E-01	6.71E-02	9.19E-01	2.76E-02
Mean	1.38E-01	1.25E-02	1.57E-01	1.22E-02
Standard Deviation	1.51E-01	1.51E-02	3.21E-01	7.80E-03
Distribution Type	LN	LN	LN	LN
Saturated Hydraulic Conductivity (K_s) in cm/s				
Minimum	2.40E-05	1.40E-05	1.40E-05	1.90E-07
Maximum	1.80E-03	4.20E-03	4.40E-02	1.30E-01
Mean	9.40E-04	1.32E-03	1.17E-02	*2.88E+00* [a]
				8.74E-05
Standard Deviation	6.90E-04	9.98E-02	8.48E-02	*9.46E+04* [a]
Distribution Type	LN	LN	LN	LN
Slope (n)				
Minimum	1.19E+00	1.26E+00	1.26E+00	1.41E+00
Maximum	2.06E+00	1.88E+00	5.06E+00	1.67E+00
Mean	1.43E+00	1.53E+00	2.18E+00	1.59E+00
Standard Deviation	2.63E-01	1.70E-01	8.94E-01	1.01E-01
Distribution Type	Neither	LN & N	Neither	Neither
Residual Moisture Content (θ_r) in cm^3/cm^3				
Minimum	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Maximum	8.44E-02	3.20E-02	9.90E-02	6.60E-02
Mean	3.75E-02	1.26E-02	2.46E-02	2.20E-02
Standard Deviation	2.93E-02	9.92E-03	1.87E-02	2.06E-02
Distribution Type	N	N	N	N
Saturated Moisture Content (θ_s) in cm^3/cm^3				
Minimum	3.37E-01	5.57E-02	1.76E-01	6.74E-02
Maximum	5.30E-01	2.14E-01	5.19E-01	2.34E-01
Mean	4.68E-01	1.61E-01	3.58E-01	1.34E-01
Standard Deviation	6.14E-02	5.96E-02	7.67E-02	5.37E-02
Distribution Type	Neither	Both	N	Both

[a] Recognizing the extreme variability in the available data, Khaleel and Freeman (1995) recommended using a geometric mean of 8.74E-05.

LN = Log Normal distribution

N = Normal distribution

Table C-5. Sediment Types and Unsaturated Flow Model Parameters Used in the Composite Analysis (Kincaid et al. 1998).

Soil Name	Code	van Genuchten alpha (-)	van Genuchten n (1/cm)	Residual Water Content (cm^3/cm^3)	Saturated Water Content (cm^3/cm^3)	Saturated Hydraulic Conductivity (cm/s)	Bulk Density (g/cm^3)	Gravel %*
East Hanford Gravel	EHG	8.11E-03	1.58	0.0146	0.119	1.76E-03	1.97	41.70%
East Hanford Sand	EHS	1.30E-01	2.10	0.0257	0.337	1.19E-02	1.78	17.30%
East Ringold	ER	8.19E-03	1.53	0.0262	0.124	3.97E-04	2.04	43.30%
West Hanford Sand	WHS	1.44E-02	2.20	0.0519	0.382	3.98E-04	1.64	3.60%
Early Palouse	WEP	6.27E-03	2.53	0.0300	0.379	9.69E-05	1.68	2.00%
Plio-Pleistocene	WPP	1.55E-02	1.78	0.0616	0.337	5.79E-02	1.65	8.40%
West Ringold	WR	3.14E-02	1.65	0.0236	0.226	5.76E-02	2.04	43.30%

NOTE: Data are from Khaleel and Freeman (1995a). A normal distribution was assumed for the parameters "van Genuchten n," "Residual Water Content," and "Saturated Water Content," and the mean was calculated accordingly. A log-normal distribution was assumed for the parameters "van Genuchten alpha" and "Saturated Hydraulic Conductivity," and the mean was calculated accordingly. If the sample size was less than 10, the parameters "van Genuchten alpha" and "Saturated Hydraulic Conductivity" were determined using the geometric mean.

* Only fine particles were assumed to contribute to sorption of radionuclides. The impact of larger particles was corrected using Gravel %.

Table C-6. Non-Reactive Macrodispersivity Estimates for Sand-Dominated Sequences of the Hanford formation in the 200 East Area.

| Formation	σ^2_{LnK}	Correlation length, • (cm)	A_L (cm)	A_T (cm)
Sandy	3.10	30	~100	10

for the Hanford sandy sequence in the 200 East Area (Khaleel 1999). The transverse dispersivities are estimated as 1/10th of the longitudinal values (Gelhar et al. 1992). The large-scale macrodispersivity estimates in Table C-6 are of similar magnitude to those (high reliability data) in Figure C-13 for length scales on the order of 100 m.

Ward et al. (1998)[3] obtained dispersivity estimates via field measurements at a location close to the ILAW site, using potassium chloride (KCl) as a tracer. Analysis of the data provided dispersivities that ranged from 1.3 to 7.8 cm for travel distances ranging from 25 to 125 cm. Dispersivity increased with depth to about 0.75 m, after which it essentially became constant. These estimates are for the Hanford formation but the transport distance within the vadose zone

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[3] Ward, A.L., R.E. Clayton, and J.S. Ritter. 1998. Determination of in situ hydraulic parameters of the upper Hanford formation. Letter Report to Fluor Daniel Northwest, Inc. December, 1998. Pacific Northwest National Laboratory. Richland, WA.

Figure C-13. Longitudinal Macrodispersivity in Saturated Media as a Function of Overall Problem Scale with Data Classified by Reliability (Gelhar et al. 1992).
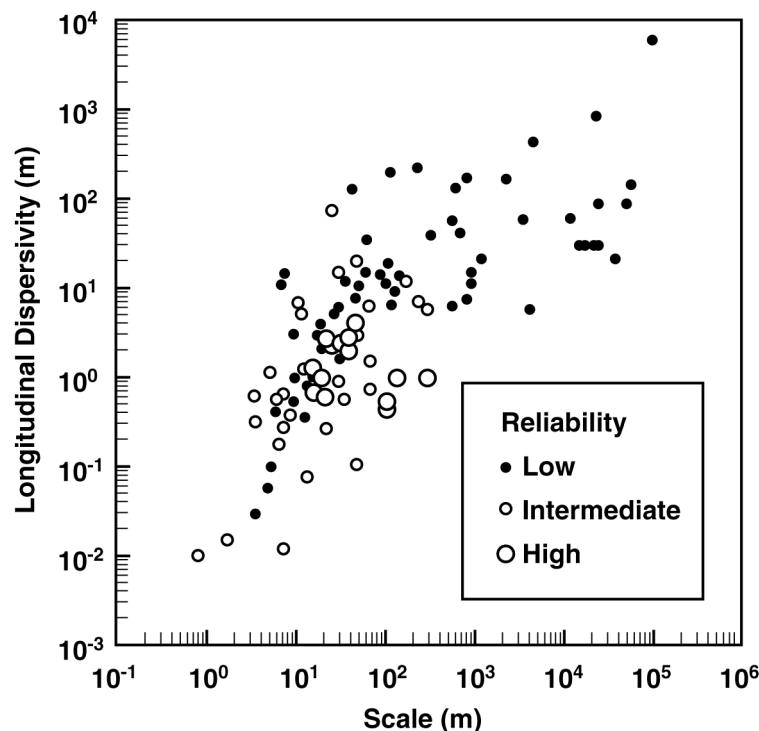

E9908123.32

is indeed of limited extent. Nevertheless, results based on the limited data are consistent with the concept of a scale-dependent dispersivity. Thus, although no data exist on large-scale dispersivities for the vadose zone, it is expected that they will be larger (as is suggested by the longitudinal dispersivity estimate of 100 cm) than those based on the small-scale tracer experiment of Ward et al. (1998).

Based on a survey of literature Gelhar (1993) presented, as shown in Figure C-14, the longitudinal vadose zone dispersivities as a function of the scale of the experiment. Figure C-14 shows a lack of data for scales larger than 2 m. Nevertheless, similar to saturated flow, Figure C-14 shows an increase of dispersivity with an increase in scale. Figure C-14 also shows results from the Ward et al. (1998) experiment; their data are in close agreement with others.

Figure C-14. Longitudinal Macrodispersivity in Unsaturated Media as a Function of Overall Problem Scale (Gelhar 1993).

[Note: The triangles are data from Ward et al. 1998.]

E9908123.26
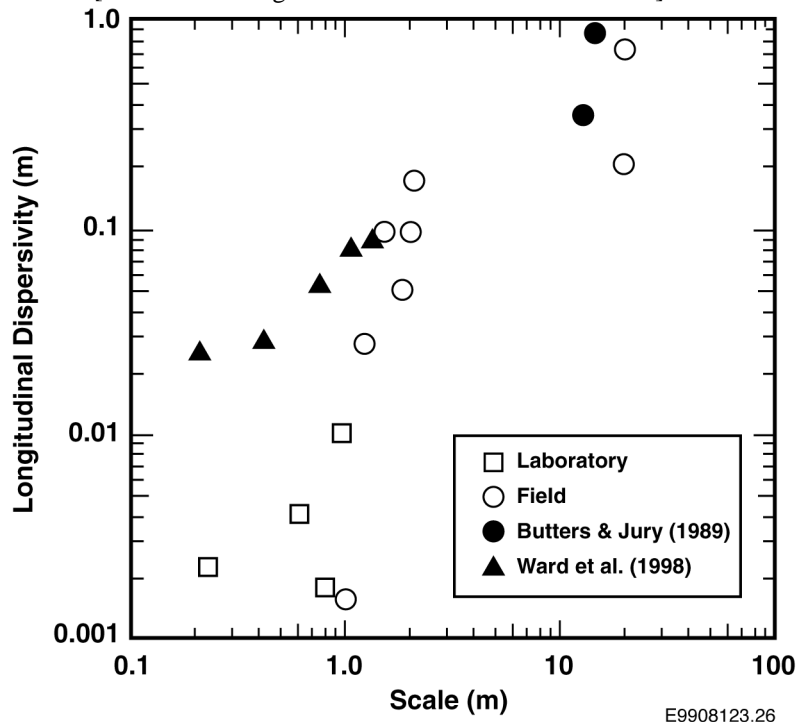
C.3.1.2.3. Geochemical Characteristics. The Hanford formation sediments consist of glaciofluvial materials predominated by quartz and plagioclase minerals (30 to 50% by weight each). Other dominant phases are K-feldspar and Mica(Biotite)/Illite at 5 to 10% by weight each. Smectite clays represent a few weight percent of the bulk sediment and predominate in the clay fraction. Hanford formation sediments are typified as having low organic carbon content ≤0.1% by weight and low to moderate cation exchange capacity (3 to 8 milliequivalents per 100 g). See Serne et al. (1993) and Kaplan et al. (1998) for more details. The sediments have a slightly basic pH when wetted (pH of saturation extract ranges from 7.5 to 8.5), and small amounts of calcium carbonate [calcite] are common and thought to be a weak buffer.

The Plio-Pleistocene sediments are generally of the same mineralogy, but with much smaller grain size and a higher proportion of clays with smectites predominating followed by small percentages of vermiculites, mica/illites, and kaolinite.

Much less mineralogy data are available for the Ringold Formation sediments but in general they are quite similar to the Hanford formation. Thin beds of caliche (with calcite predominating and variable amounts of ferric oxide) exist in the 200 West Area in the Plio-Pleistocene above the Ringold Formation. Calcic/ferric oxide cements are often present deeper within the Ringold Formation. The cementing can alter significantly the permeability of the otherwise coarse-grained Ringold sediments.

Contaminant adsorption reactions with the Hanford formation, Plio-Pleistocene, and Ringold Formation sediments are fairly well characterized for dilute waste solutions and groundwater. An adequate database also exists for high ionic strength waste solutions, with slightly acidic to slightly basic pH values. A small database exists for the combined high ionic-strength/highly basic tank liquors for many common radionuclides. The K_d data are well tabulated in the Composite Analysis (Kincaid et al. 1998), Serne and Wood (1990), and Kaplan et al. (1995a, 1996, 1998). Adsorption is assumed to be the controlling geochemical process in most instances, but neutralization of acid wastes by the alkaline sediments and neutralization of basic tank wastes certainly causes precipitation of some macro and many minor contaminant species within the sediment pores. Outside the zone of pH neutralization, adsorption is considered to dominate in the vadose zone.

The geochemical processes that affect contaminant migration and mineralogy of the vadose zone sediments for the 200 East and 200 West Area are quite similar. Some subtle changes must be considered, as the fine-grained sediments and caliche zones above the Ringold Formation are less prevalent in the 200 East Area. Adsorption is somewhat lower in the 200 East Area down the whole vadose zone profile because of the lack of distinct fine-grained beds and caliche layers, but the magnitude of the decrease is not generally considered significant.

C.3.1.2.4. Important Features Affecting Vadose Zone Transport in the 200 Areas.
Hydraulic and geochemical properties of Hanford Site sediments are considered highly variable, both between the various units and within each hydrostratigraphic unit. Because the geometry and configuration of sedimentary, hydrologic, and geochemical facies and heterogeneities cannot be completely defined, the effects of these features will most likely have to be captured via sensitivity or uncertainty analyses. Underestimating the degree of small-scale stratifications and variations in texture will likely lead to an underestimation of lateral spreading, which could lead to either an overestimation or underestimation of the predicted penetration depth and rate of transport.

Preferential flow could take place along natural or man-made structures (e.g., clastic dikes, well casings), or as induced by flow instabilities.

C.3.1.2.5. Options for Vadose-Zone Transport Model in 200 West Area. A representative
flow and transport model of the vadose zone within the 200 West Area should consider the following features:

- At least six hydrostratigraphic units over cumulative thicknesses ranging from 50 to 80 m, and their site-specific ranges in physical and chemical properties (based on available geologic, soil physics, and geochemical data from nearby boreholes and outcrops)

- Preferential pathways, including interconnected clastic dikes (more frequent in the fine-grained facies of the Hanford formation) and foreset cross bedding in the Hanford formation coarse-grained facies

- The high moisture retention capacity of the Early Palouse Soil

- Vertical flow along fractures and/or lithologic discontinuities within the reactive Plio-Pleistocene (caliche) unit

- Lateral spreading along multiple strata with contrasting physical properties (e.g., bedding contacts). This is particularly prevalent (every meter or less vertically) within fine-grained facies of the Hanford formation, but also occurs atop the Plio-Pleistocene unit, and atop silt and/or clay lenses within the Ringold Formation.

C.3.1.2.6. Options for Vadose-Zone Transport Model in 200 East Area. A representative multidimensional flow and transport model of the vadose zone within the 200 East Area should consider the following features:

- At least five hydrostratigraphic units over a cumulative thickness of up to 100 m and their site-specific ranges in physical and chemical properties (based on available geologic, soil physics, and geochemical data from nearby boreholes and outcrops)

- Preferential pathways, including interconnected clastic dikes (more frequent in the fine-grained facies of the Hanford formation) and foreset cross bedding in the Hanford formation coarse-grained facies

- Lateral spreading along multiple strata with contrasting physical properties (e.g., bedding contacts). Particularly prevalent within the fine-grained facies, lenses, and paleosols in the Hanford formation, but also atop silt and/or clay lenses within the Ringold Formation

- Sublinear to anastamosing channel cut scour and fill features within the Hanford formation, which could act as preferential pathways in the horizontal direction

- Tilted beds of the Ringold Formation. Beds dip gently to the south (slope = 1.1 degrees). Angular unconformities exist with the overlying horizontal beds of the Hanford formation.

C.3.1.3. 300 Area. The vadose zone beneath the 300 Area is generally about 40 to 50 ft. thick.

C.3.1.3.1. Hydrostratigraphy. The geology of the vadose zone consists almost entirely of the Pleistocene Hanford formation with a thin veneer of Holocene eolian sand. Thin portions of the Ringold Formation may also extend above the water table in portions of the site.

Schalla et al. (1988) described the eolian sand deposits as ranging from 0 to nearly 15 ft. thick. Missing deposits are thought to have been removed by construction activities, and often replaced by or covered with construction gravel. The geologic contact with the underlying Hanford formation is quite distinct.

Schalla et al. (1988) described the Hanford formation as poorly sorted sandy gravel with some silt and local sand stringers. The upper portion was described as containing pebble to boulder gravel that grows finer with depth. The gravel fraction is described as mainly basaltic in nature

with some quartz-rich and metamorphic clasts. The thickness of the Hanford formation varies from 21 to 81 ft.

Gaylord and Poeter (1991) describe the Hanford formation beneath the 300 Area as consisting predominantly of three lithofacies: Gravelly Sand, Sandy Granule to Pebble Size Gravel, and Sandy Cobble to Boulder Size Gravel. They further indicate that fine-grained sand facies, comprising only a minor percentage of the 300 Area Hanford formation deposits, are concentrated in the southern part of the area intermixed with the coarse-grained gravel dominated deposits.

In an attempt to define the spatial distribution of hydrologic properties (primarily aimed at the unconfined aquifer) Gaylord and Poeter broke the 300 Area sediments into four general hydrofacies. These hydrofacies were defined based on grain size and sorting, recognizing the importance of the fine-grained component to hydraulic behavior.

C.3.1.3.2. Hydraulic Characteristics. Schalla et al. (1988) presented the results of physical (e.g., field moisture content, water retention, particle-size analysis) and bulk geochemical analyses of selected samples. The field water content ranged from <2 to nearly 5% by weight. Due to the lack of site-specific data, representative values for other important hydrologic parameters must be derived from Khaleel and Freeman (1995b); refer to Section 3.1.2.2.

C.3.1.3.3. Geochemical Characteristics. Gaylord and Poeter (1991) also provided whole rock geochemical (via X-ray fluorescence) and rare earth/trace element (ICP/MS) analyses for the Hanford and Ringold Formations. These data show no striking differences to similar data for 200 Area Plateau sediments. Existing sorption data are unavailable for the 300 Area; therefore, sorption parameters must be derived from an assessment of the waste chemistry and existing sorption values from other Hanford Site sediments (similar to the selection process used in the Hanford Composite Analysis [Kincaid et al. 1997]). The mineralogy and contaminant adsorption properties of the Hanford Formation sediments in the 300 Area are thought to be quite similar to those in the 200 Areas, such that the extensive K_d database should be adequate to the SAC (Rev.0) needs.

C.3.1.3.4. Options for Vadose-Zone Transport Model in 300 Area. Based on the available geologic information for the 300 Area, a representative geologic model of the vadose sediments here should include at least four or five different units. These would represent 1) backfill (or surface cover); 2) eolian sands (if still present at the waste site); 3) sand-dominated Hanford sediments; 4) gravel-dominated Hanford sediments; and 5) gravel-dominated Ringold sediments (if present above the water table). Although these sediments are primarily coarse, it must be recognized that some silt stringers are present, particularly in the Hanford formation. The location and extent of these stringers is uncertain. Some degree of heterogeneity and anisotropy is also present in each unit; however, there is insufficient data to adequately portray these characteristics. Because the geometry and configuration of various facies and heterogeneities cannot be adequately portrayed, the effects of these features will most likely have to be captured via sensitivity or uncertainty analyses, within the context of the larger hydrostratigraphic units. Not accounting for small-scale stratifications and variations in texture will likely lead to an underestimation of lateral spreading and either overestimating or

underestimating of the predicted penetration depth/rate. For example, sloping layers may increase lateral spreading, but may also reduce travel time to the aquifer by concentrating (funneling) the flow.

Those sites away from the river (i.e., outside the zone of river stage influences [bank storage]) might be best portrayed as a 1-D stratified soil column. Those sites near the river, particularly near critical habitat, may require additional detail supported by 2-D or 3-D soil columns. Natural short circuiting flow paths (e.g., clastic dikes, fractures, etc.) are not known to occur in the 300 Area; however, preferential flow along well casings or other engineered structures, or as induced by flow instabilities, may be important and should be addressed on a case-by-case basis.

The hydraulic and geochemical properties of the geologic media of the 300 Area are also poorly defined. Without site-specific data, values for the hydraulic properties will have to be estimated from grain-size data, pulling those values from Khaleel and Freeman (1995a). This approach also assumes that the relationships between moisture content, pressure head, and unsaturated K are nonhysteretic, and can be represented by those of van Genuchten (1980) and Mualem (1976). Initial moisture conditions are likely to be based on steady-state simulations under natural recharge conditions. Infiltration from liquid disposal sites should represent the best estimates developed from process knowledge, discharge records, and the inventory/release models. The wetted cross section (width) of 1-D soil columns would have to be adjusted to account for the volumes and rates of discharge, and the K_{sat} of the finest (least conductive) strata (similar to the approach used in the CA).

Without site-specific geochemical data, values for the geochemical properties (i.e., K_ds) will have to be estimated from the sediment type (e.g., grain-size data and the presence of secondary mineralization like the Fe oxide coatings often found in the Ringold Formation) and waste type, pulling from existing laboratory measurements. Where high concentration, alkaline, or acidic wastes have been discharged, some form of time-varying change in mobility must also be accounted for. This might be accomplished using a multitude of different K_ds to represent the sorptive capacity of the soils as the waste becomes more diluted and/or buffered by meteoric recharge and waste sediment interactions (i.e., mimicking the decrease in competing ions along the flow path). Another option in some critical cases may be fully reactive transport (provided data can be obtained to adequately characterize the controlling features and processes).

C.3.2 Processes

The conceptual model of the vadose zone for SAC (Rev. 0) includes the following:

- Nature and quantity of contaminants released intentionally and unintentionally to the vadose zone

- Nature and quantity of contaminants retained (stored) within the vadose zone

- Mechanisms, rates, and routes by which contaminants move (or are moved) through the vadose zone to the water table

- Fate of contaminants within the vadose zone.

Other elements of the SAC address the details of the nature and quantity of contaminants released to the vadose zone. The focus of this element is on the movement (i.e., the mechanisms, rates, and pathways) and fate of those contaminants while in the vadose zone. The possible impacts of each are briefly described in this section.

C.3.2.1. Transport Mechanisms. For the majority of contaminants, movement through the vadose zone is contingent on being dissolved within flowing water. The primary source of flowing water is precipitation that has infiltrated below the zone of evaporation and the influence of plant roots. Such water eventually flows to the water table, carrying with it whatever dissolved species may be present. Gee et al. (1992) presented evidence from multiple experiments showing that measurable diffuse natural recharge occurs across the lower elevations of the Hanford Site, with rates ranging from near zero in undisturbed shrub-steppe plant communities to more than 100 mm/yr beneath the unvegetated graveled surfaces of tank farms.

On a local basis, the possibility exists for the recharge rate to be much higher. Variations of topography can focus infrequent surface runoff in such a way that infiltration is greater and occurs in a shorter time. Water runoff from the higher elevations occurs intermittently, but can be extensive (Pearce et al. 1969). Cushing and Vaughan (1988) indicate runoff from higher elevations has a 3.8-year return period. Extensive water runoff does not appear prevalent at the Hanford Site between Highway 240 and the Columbia River, based on the absence of geomorphic features such as erosion rills and gullies. However, observations have revealed that local runoff does occur when there is a heavy rain, quick snowmelt, and the ground is frozen (Jones 1989, Ward et al. 1997).

Another source of water for transporting contaminants originates from industrial activities. Historically, millions of gallons of contaminated water were disposed to subsurface infiltration structures and surface ditches and ponds. Such unregulated disposal ceased several years ago. Currently, two facilities are permitted to discharge to the vadose zone: the State-Approved Liquid Disposal (SALD) Facility and the Treated Effluent Disposal Facility (TEDF). Discharges from these facilities are closely monitored and regulated. Numerous discharges of water, collectively called miscellaneous streams, are also permitted but do not need to be monitored unless they exceed certain discharge rates and annual amounts (DOE-RL 1998). These streams include hydrotesting, maintenance, construction, cooling water and steam condensate, and storm water control. Also unregulated but possible sources of additional recharge water are roads, road shoulders, parking lots, power and fire lines, and all structures that do not have precipitation controls that fall under the Miscellaneous Streams permit. Waste management operations have also contributed unintentional releases of water, primarily through events such as spills, tank leaks, and distribution pipe leaks.

Some contaminants (as well as water) are volatile and move in the gas phase. The bulk of this movement is diffusional, but convective flow can occur near the soil surface and near open boreholes in response to barometric changes. Remediation activities (e.g., vapor extraction, thermal treatment) can also affect local convective gas flow.

The geothermal gradient has a small but steady impact on the movement of water upward through the vadose zone. Enfield et al. (1973) used field measurements of temperature and matric potential just south of the 200 East Area to calculate an upward water flux of 0.04 mm/yr.

C.3.2.2. Transport Rates. Fluids such as water move through the vadose zone at rates determined by the hydraulic, thermal, and vapor gradients and the relevant properties of the sediments. For many applications, common (and mostly valid) assumptions include a static air phase, isothermal conditions, and no density effects. With these assumptions, flow rates are calculated using Richard's equation with gravity and capillary potential gradients. When these assumptions are not appropriate (e.g., organic liquids, vapor flow, hot saline tank waste), more sophisticated equations must be used to calculate rates.

The rate of recharge at a particular location is influenced by five main factors: climate, soils, vegetation, topography, and springs and streams. Other factors can significantly impact recharge by affecting one or more of the main factors. These factors include soil development, animal activity, fire, water and wind erosion and deposition, plant community changes, disturbance, and human structures (e.g., roads, buildings). The rate of recharge at each waste site will depend on the design of the surface cover. Plants and animals live within the upper 1 to 2 m of soil, and some plant roots can reach depths of 3 m. Surface covers can be designed to protect against such intrusion by including biobarriers, which are layers that resist biotic intrusion. Coarse gravel layers have been shown to be ineffective at preventing root and insect intrusion, but they appear to deter animal intrusion. For thinner cover designs, the biobarrier may be closer to the surface and more susceptible to degradation. Intrusion of surface covers by plants and animals can create macropores that could become conduits for surface water to flow into the soil much deeper than expected. Inadvertent intrusion by humans can result in surface depressions that could become areas of focused recharge when surface runoff occurs.

Some of the liquids that were disposed or leaked to the vadose zone had properties that differed significantly from the properties of pure water. Because their properties differed from those of water, their rate and route of movement through the vadose zone may differ from those of water. The specific gravity of wastes that have leaked from single-shell tanks ranged from 1.1 to 1.65, which could enhance the transport of contaminants. Increased density has been demonstrated to elongate contaminant plumes vertically and reduce lateral spreading caused by stratigraphic variations in hydraulic properties (Ward et al. 1997). The properties of these fluids will change as contaminants are diluted, sorbed, or evaporate into the sediment air space.

Organic fluids were also disposed at the Hanford Site. The movement of these fluids through the vadose zone and groundwater aquifer is complex because they involve flow in multiple phases: the organic liquid phase, the dissolved phase in water, and the vapor phase in the vadose zone air space. The movement of organic fluids can be enhanced if their density is much higher than the density of water. That is the case for the primary organic fluid contaminant at the Hanford Site, the DNAPL carbon tetrachloride. Between 1955 and 1973, roughly 570 to 920 Mg of carbon tetrachloride were disposed to three subsurface infiltration facilities at the Hanford Site in Richland, Washington (Rohay et al. 1994). The current groundwater plume containing concentrations above 0.5 mg/L covers an area of about 11 km^2. Soil vapor extraction and pump-and-treat activities have been employed to prevent further movement of the plume and reduce contaminant mass. Efficiencies of the vapor extraction activities have decreased. The pump-

and-treat activities may be having an impact, because the plume extent has not increased. The behavior of carbon tetrachloride in the subsurface and in the vadose zone is poorly understood and requires additional characterization and assessment to determine the important processes governing its fate and transport.

The rate of gas movement in the vadose zone will be affected by the magnitude of any temperature gradients. The vadose zone across the entire Hanford Site experiences temperature changes that arise from the diurnal and seasonal temperature changes at the soil surface. The magnitude of the temperature changes diminishes with depth; at 10 m, the seasonal change appears to be less than 1°C. Near-surface temperatures appear to have a minimal effect on recharge rates if the rates exceed 10 mm/yr, but they could be important when rates are less. In addition to the near-surface temperature changes, a steady upward geothermal gradient exists that drives gas (and water vapor) upward. The elevated temperatures of the leaked waste from the single-shell tanks and previous operational discharges could have induced local movement of both liquids and vapor.

The formation of colloids and occurrence of colloid-facilitated transport of contaminants were identified by the Expert Panel as a potentially important process for the vadose zone (DOE 1997). For most waste sites at the Hanford Site, the low water contents and simple geochemistry are not conducive to colloid formation or colloid-facilitated transport. However, for the large-volume discharges and the leaking tank wastes, the conditions existed for both colloid formation and colloid-facilitated transport. However, little or no data exist at the Hanford Site to adequately characterize the potential for colloidal transport under these conditions.

C.3.2.3. Transport Pathways. Because gravity is the dominant force operating to move liquids downward, the predominant route for contaminant movement is downward. Variations in the hydraulic properties and the presence of impeding features (i.e., caliche layers and disposal facilities) can locally alter and redirect the movement laterally. Various preferential pathways (i.e., clastic dikes and fractures) are capable of concentrating or contributing to phenomena such as fingering and funnel flow. Preferential flow has been documented along poorly sealed well casings at the Hanford Site (Baker et al. 1988), and transport along clastic dikes has been postulated to be potentially important (DOE 1997). Relatively simple stratigraphic layering gives rise to more complex water content distributions and enhanced lateral spreading that impedes vertical migration of contaminants.

Because of the nature of some wastes, the local routes of contaminant movement will vary. The Vadose Zone Expert Panel (DOE 1997) stated that the likely mode of transport for leaked or disposed tank waste in the Hanford Site geology is along preferential, vertical, and possibly tortuous pathways. They identified possible preferential flow caused by the following:

- Hot (350°F) caustic tank waste leaking into the vadose zone, flashing to steam, fracturing the matrix, and enlarging pores

- Hot (350°F) caustic tank waste leaking into the vadose zone with a self-healing nature, creating geothermal convection systems that could move contaminants upward and the hot alkaline slurry reacts with Hanford Site sediments

- Dissolution of siliceous sediments by the hot and alkaline tank wastes, which could increase porosity in some places (by dissolution) and lower porosity in others (by precipitation).

C.3.2.4. Contaminant Behavior. The fate of contaminants in the vadose zone depends on geochemical conditions, the speciation of the contaminant, residence time, and microbial activity.

Sediments have the capacity to sorb most contaminants from solution. The amount of sorption is a function of many factors, including mineral surface area and type, contaminant type (speciation) and concentration, overall solution concentration, pH, Eh, and reaction rates for the controlling adsorption or precipitation, dissolution, and hydrolysis reactions.

Some contaminants do not sorb at all (i.e., soluble anions such as nitrate, chromium [VI] [Cr(VI)] and technetium oxide [TcO_4^-]) and are moved along with the bulk solution. The movement of contaminants through the vadose zone is affected by their sorption in the far-field and sometimes by complex dissolution/precipitation reactions between waste liquids of extreme pH and the slightly alkaline sediments in the near-field. The significance of sorption is that it delays downward movement of the contaminant and allows degradation processes to occur (e.g., radioactive decay), and for some, rather irreversible incorporation into the sediment. Sorption can be described using a simple linear relationship (i.e., a distribution coefficient or K_d) that is determined empirically. Values of K_d have been measured for a wide range of contaminants and waste types at the Hanford Site (Kincaid et al. 1998). The K_d approach has been applicable for most analyses at the Hanford Site because contaminant concentrations have been low and the chemistry has been simple. However, conditions near some waste sources are so strongly influenced by the chemistry of the waste that the K_d approach may not be applicable. Such is the case for the hot, highly concentrated tank wastes in contact with the Hanford Site sediments. The general consensus is that these wastes will likely decrease the sorption of normally sorbed contaminants (e.g., cesium-137). The net effect is an increase in their mobility until concentrations in the sediments decrease to the range appropriate for the K_d approach. The complicated pH neutralization reactions that occur with highly acid, and more importantly for the Hanford Site, highly basic wastes with sediments is being studied. Future SAC revisions will determine whether more complicated chemical reaction processes need to be modeled to more accurately determine the migration rates of key contaminants of concern.

Contaminants that exist in the gas phase (e.g., radon, carbon-14, carbon tetrachloride) are subject to atmospheric venting and remediation activities (i.e., vapor extraction). Carbon-14 as carbon dioxide also reacts strongly with alkaline earth cations to form insoluble carbonates at neutral to basic pH values. Further, carbon-14 reacts rather irreversibly with cement, a common waste form, container or structure used in many solid waste burial grounds to form carbonate precipitates (Krupka and Serne 1996, Serne et al. 1992).

Contaminants near the soil surface are subject to animal and plant uptake. Plants and animals live within the upper 1 to 2 m of soil, and some plant roots can reach depths of 3 m. Wastes present within this zone are subject to ecological uptake and dispersal above ground.

Contaminants that are consumed by microbes are subject to degradation into other compounds that may or may not be considered contaminants. This degradation process depends on the presence of a microbial population that is capable of degrading the contaminant(s) in question and the availability of any additional nutrients that may be required for the microbes to be effective.

Sometimes it is the water that is consumed rather than the wastes. Waste forms such as the ILAW undergo a corrosion process that consumes water. In a dry disposal, this consumption process will create a water vapor gradient that draws vapor toward the waste form.

C.3.3 Events

Various events to be considered in the conceptual model include those that are naturally occurring (e.g., meteoric recharge), those that are man-made (e.g., intentional or unintentional contaminant and water releases), those that occur slowly over a long period of time, and those that represent extreme or unusual occurrences (e.g., 500-year storms, volcanism). The important types of events that should be considered are summarized in Section 3.3.1 through 3.3.7.

C.3.3.1. Recharge Events. Each precipitation event has the potential to contribute to recharge. This type of recharge can occur in the natural ecosystem as either diffuse or focused recharge, as well as within and around industrial facilities. How much each event contributes is site- and event-dependent (see earlier discussions on factors affecting recharge). Two facilities are currently permitted to discharge waste to the vadose zone. Numerous discharges of water, collectively called miscellaneous streams, are also permitted but do not need to be monitored unless they exceed certain discharge rates and annual amounts. These streams include water testing, maintenance, construction, cooling water and steam condensate, and storm water control. In the past, a number of facilities discharged wastes to the ground at the Hanford Site.

Unintentional releases include spills, tank leaks, and distribution pipe leaks.

C.3.3.2. Source/Release Events. Source events include all accidental or intentional discharges of fluids, gases, and contaminants to the environment. These events must be characterized for quantity, quality, duration, and phases of wastes or fluids released. These events also include remediation activities that involve the injection of liquid, chemicals, and gases, and the injection of heat.

C.3.3.3. Discharge/Exit Events. Discharge events include all actions to remove fluids, gases, and contaminants from the environment. These events must be characterized for quantity, quality, duration, and phases of wastes or fluids removed. These events include remediation activities such as groundwater pumping, vapor extraction, and heat removal (e.g., cryogenic barriers).

C.3.3.4. Climate Events. A change to a drier and/or warmer climate could result in a sparser plant community, a change in the mix of plant and animal species, and increased wind erosion and deposition (e.g., reactivated sand dunes). The stress of this change could allow non-native plant and animal species to supplant native species.

C.3.3.5. Volcanism. Volcanic activity has the potential to deposit significant quantities of ash. Such deposition could reduce evaporation and plant activity for years, which could increase the natural recharge rate.

C.3.3.6. Flooding Events. Natural flooding in the Columbia River is predicted to affect low-lying areas along the river but not the 200 Areas. Failure of the upriver dams has the potential to affect the entire Hanford Site. The probable maximum flood in the Cold Creek drainage basin could affect the southwestern portion of the 200 West Area (Skaggs and Walter 1981). Under this scenario, water from the flood would reach the Yakima River.

C.3.3.7. Human Disturbance Events. Human activities are capable of degrading surface covers over waste sites and exposing the wastes to increased recharge and more direct contact with the biosphere.

C.4   DEALING WITH UNCERTAINTY

The proposed SAC (Rev. 0) uncertainty approach is a Monte Carlo technique that has the following major attributes:

- Specialized sampling techniques would be employed to reduce computation time.

- Complex or moderately complex models would be linked together into a system model.

- Release and transport calculations would be conducted and the results stored for later use by risk and impact models.

More discussion on this overall approach is provided in Appendix G.

Implementation of this Monte Carlo approach would require running multiple simulations with the vadose zone model. In the SAC (Rev. 0) a small subset of model parameters would be described using statistical distributions. Five parameters that could be varied in a statistical fashion are provided in Table C-4. Other parameters, such as the thickness of geologic layers, or the timing of events (such as increased precipitation), could also be varied. If more than one conceptual model for the vadose zone became available, the proposed approach could incorporate conceptual model uncertainty as well as parametric uncertainty.

The Monte Carlo approach yields a suite of model results that is passed to the saturated zone model. This data transfer supports uncertainty analyses in later model components, and in the final risk and impact metrics. In addition, uncertainty in the vadose zone results could be described both qualitatively and quantitatively as a stand-alone analysis.

C.5   ASSUMPTIONS/TECHNICAL RATIONALE

One of the purposes of the initial SAC (Rev. 0) is to demonstrate that an assessment of the scale and scope of the Hanford Site and the Columbia River can be conducted. The large scale and complexity of a cumulative effects assessment for the Hanford Site (particularly the initial demonstration [SAC Rev. 0]), together with the lack of detailed characterization data and/or understanding of some of the detailed fate and transport processes, necessitates simplification of the site features, release events, and the contaminant fate and transport processes. Thus, this first demonstration (Rev. 0) is focused on contaminants representing a range of mobility classes released from representative waste types. Similar waste types will be aggregated by area, and by contaminants transported via the principal pathway of concern (i.e., through the vadose zone to the groundwater and then to the Columbia River). Sensitivity and uncertainty analyses will be demonstrated for capturing the magnitude of impacts that specific contaminants, release events, features, or processes have on the overall migration of contaminants.

Four radionuclide mobility groups and two chemicals have been selected to represent the expected range in sorption and transport properties for the primary contaminants of concern at the Hanford Site. These initial contaminants include the following:

- Highly mobile radionuclides (e.g., tritium [hydrogen-3] and technetium-99)
- Slightly mobile radionuclides (e.g., iodine [iodine-129] and uranium)
- Immobile radionuclides (e.g., cesium-137 and strontium-90)
- Highly immobile radionuclides (plutonium-239/240)
- Carbon tetrachloride
- Hexavalent chromium.

The inventory for these constituents will be composited for representative waste types within a given waste management area (e.g., all SSTs within the 200 West Area), and the waste release model(s) will provide input to the vadose zone model(s) in terms of the temporal mass flux and concentrations released. The number of waste types to be included in the SAC (Rev. 0) has yet to be determined, but is assumed to be in the range of 4 to 8. These might include the following:

- Dry waste burial grounds
- SSTs
- Specific retention trenches
- High-salt acid waste cribs
- Low-salt, low acid waste cribs
- Cooling water ponds and ditches.

The primary waste disposal areas in focus for the SAC (Rev. 0) include the following:

- A composite of the 100-N and 100-D Areas
- 200 East Area

- 200 West Area
- 300 Area.

The principal transport pathway to be tested in the SAC (Rev. 0) is through the porous media of the vadose zone via aqueous phase transport.

C.6   OUTSTANDING ISSUES

Many issues and sources of uncertainty affect the ability to predict the behavior of contaminants in the vadose zone. These issues include scale effects, spatial resolution of data, preferential flow, funneled flow, colloid transport, density effects, and thermal effects. Many of these issues cannot/will not be addressed until later revisions of the SAC, and then some only after resolving key issues through the science and technology program.

C.6.1 Effects of Scale

Some of the greatest difficulties are related to understanding the effects of scale (i.e., spatial, process, temporal, observational, and modeling or assessment). There is a lack of understanding regarding how vadose zone processes (at various spatial and temporal scales) interact, which ones are dominant, and how these interactions can be related to and interpreted from existing field and/or laboratory observations. This also relates to what must be measured and modeled to assess both risk and the ability of the models, along with the characterization and observational data to assess the risk within useful uncertainty bounds (i.e., the validity of the models). Discussions of outstanding issues are generally focused on performance/risk assessment under future conditions and future releases. However, there are also site characterization and laboratory study needs related to interpreting observations from past tank leaks, spills, and nearby deliberate discharges. This information is important for estimating existing inventories for use as initial conditions, and also to allow some degree of demonstration of the validity of our understanding and the predictive ability of the models used for flow and transport of tank wastes. This is a difficult issue because there is much about the history and character of the leaks, spills, and water losses that is difficult to characterize with a reasonable level of uncertainty. This level of uncertainty will always hamper the ability of models to predict observed distributions of contaminants in the vadose zone, even if the distributions were well known.

In past assessments, the hydrogeologic units are generally assumed to be homogeneous and isotropic in character, although in reality, these units display very complex inter- and intra-sedimentary structures at various scales. The effects of these complex structures are generally thought to enhance lateral spreading and impede downward migration. However, some of these structures might also promote "funneled flow" and/or the development of "fingered flow". Thus, the effect of these small-scale structures must be more thoroughly understood and properly accounted for in the assignment of physical properties (e.g., effective permeability, porosity, moisture retention characteristics, anisotropy, dispersivity) to the larger modeled units. The effects of small-scale structures on larger scale effective flow and transport parameters also need to be assessed to understand uncertainty and to make appropriate choices for bounding calculations, and to determine the effects of simplification on assessment predictions.

It is also important to develop the means necessary to determine effective values of parameters from small-scale (often disturbed) borehole samples in conjunction with soft information on the fine-scale structure of these sediments, and to "scale up" these values. Data will be lacking for much of the vadose zone where the analysis will be focused. Scale-up and volume averaging will be required. The justification of upscaling and averaging will need to be evaluated either deterministically or by way of a probabilistic assessment that clearly reflects the uncertainties involved in the analysis.

C.6.2 Spatial Resolution of Site Data

The scale of resolution on the nature and extent of various hydrogeologic units beneath a given waste site, based on borehole samples, is generally on the order of 5 ft vertically and 10s to 100s of feet horizontally, and the general thickness of discernable fine-grained units is thought to be on the order of 6 in. or more. It is also often the case that the internal structure of these sedimentary units has been lost in the drilling and sampling process. Vertical borehole data alone cannot provide the quality and quantity of data needed for accurate analysis of vadose zone transport. Thus, much of the knowledge on the internal structure and heterogeneities of these units comes from extrapolation of qualitative examination of "representative" outcrops. At the Hanford Site, only a few limited geostatistical studies have been conducted to quantitatively describe the internal structure and heterogeneities in outcrop and core samples. Thus, in many cases there is currently a lack of site-specific data to support the development of detailed 3-D geologic models for a given waste site.

C.6.3 Preferential Flow

Preferential pathways are important for contaminant transport associated with tank-farm releases and/or other low-volume discharges where mobile constituents have not yet been flushed through the vadose zone. However, it is important to differentiate between structurally controlled flow and unstable flow. Structurally controlled flow occurs when the structure of the porous medium or the presence of a buried structure (e.g., tank) routes the water along a "preferential path". Unstable flow or wetting-front instability occurs during infiltration when an instability develops at the fluid-fluid interface (e.g., water-air, DNAPL-water).

C.6.3.1. Structure Controlled Flow. Preferential flow is greatest when the preferred flow path consists of a series of connected large pore spaces. Because flux scales to the fourth power of the pore radius, large pores transmit very large quantities of fluid, but only when the pores are filled. Thus, water content determines the effectiveness of preferred pathways to conduct water. When water contents are high (at or near saturation), preferred pathways can conduct copious quantities of water. When water contents are low (dry vadose zone), preferred pathways with large pores do not conduct water because they cannot fill with water.

Whenever there are variations in sediment properties, the potential exists for water flow to be affected. The capillary barrier effect is a good example. The arrangement of fine-textured material over coarse-textured material temporarily delays the downward migration of water and allows it to be evaporated and transpired back into the atmosphere. The net effect is that deep

drainage is reduced. Such textural breaks are used for surface covers, but they also occur naturally throughout the vadose zone. When such "capillary breaks" are sloped, the water that is detained above the break can move laterally. In fact, this feature has been used to improve the performance of waste disposal facilities in the vadose zone (Frind et al. 1977).

Clastic dikes and unsealed boreholes can act as preferential flow paths for saturated flow by providing large connected pore spaces. These features are especially effective as preferred pathways when they cross-cut the normally horizontally layered sedimentary sequences. The actual influence of clastic dikes on flow is somewhat uncertain; however, some portions of clastic dikes have large connected pore spaces, and other portions have fine-grained clay skins that may actually limit high rates of lateral flow. Wood et al. (1995, 1996) and Jacobs Engineering Group, Inc. (1999) suggested that both clastic dikes and unsealed boreholes were insufficiently large and continuous to be significant with respect to the overall contaminant mass transport through the vadose zone. However, there are insufficient data on the actual locations and properties of these potential preferential flow paths to resolve this issue and support predictive modeling.

C.6.3.2. Unstable Flow. Unstable flow fingering develops when a saturated fine-grained textured soil overlies a coarse-grained soil. Water accumulates in and over the fine-grained unit until the thickness of the perched water provides sufficient driving force to allow the water to "drip" into the large pore spaces of the underlying coarse-grained sediment. This situation results in fingers with inner cores that are saturated surrounded by an unsaturated layer. However, fingers that are clearly caused only by the instability of a wetting front have been primarily observed in the laboratory. There is a commonly held belief that unstable flow or fingering may be an artifact of the uniform, horizontal, and homogeneous layers (e.g., glass beads) used in the laboratory experiments. The phenomena may or may not occur in natural structured geologic media. If it does, the questions that need to be addressed are as follows:

- What effect does the fine-scaled structure, which typically involves alternating coarse-grained and fine-grained layers, do to enhance or deter the formation of unstable flow fingers?

- How does this fine structure change the scale of fingers and the relative speed up of the transport process (i.e., the effect of the bypassing)?

Hendrickx's and Yao (1996) experiments found that at low infiltration rates wetting fronts stabilize because under these conditions capillarity dominates over gravity; thus, there is no mechanism to cause instability and no fingers form. They further found an increase in the number and a decrease in the size of fingers as the infiltration rate increased. Similar studies are needed to address finger formation and its scale when there are gravity-enhancing (e.g., high density fluids) and/or gravity-detracting conditions (e.g., hot liquids).

C.6.3.3. Temporal Effects. In dry environments, deep vadose zone flow (i.e., recharge to the aquifer) can be dominated by the extreme transient events (e.g., snowmelt and run-on events) if they result in saturated or nearly saturated conditions in regions with fast preferential pathways. Proper assessment of deep recharge and effects related to enhanced transport down borehole

annular space or any near surface preferential pathways and/or man-made structures must be addressed at a higher resolution both spatially and temporally. How spatial and temporal variations (particularly the extreme events) interact with heterogeneity and interfaces (particularly sloping ones with breaks or holes) to change the pathway and rates needs more investigation. The effects of geologic complexity and the spatial and temporal complexity of adjacent, interacting sources (e.g., water line leaks, fire hydrant flushing, adjacent cribs, etc.) have also not been adequately addressed.

C.6.3.4. Funneled Flow Coupled with Colloid Transport. The TWRS Expert Panel (DOE 1997) hypothesized that structure-controlled flow, coupled with colloid transport, was the most likely mechanism to move large quantities of contaminants (i.e., cesium-137). If this combination of processes is important to the transport of risk-important contaminants, then this combination of processes needs to be investigated.

C.6.3.5. Temperature and Density Effects. Other important issues raised by the TWRS Expert Panel relate to how the hot (350°F) caustic tank leak waste interacts with the geohydrologic system through time to effect both the fluid movement and contaminant transport processes. Many of the heat effects related to the high temperatures of the tanks, the elevated temperatures surrounding the tanks, and the self-heating nature of the leaked wastes, have yet to be investigated and resolved.

The high heat load of the SSTs, coupled with vapor transfer, could potentially set up a system whereby soluble briny wastes, leaked from the tank, could migrate toward the heat source (e.g., center of the bottom of the tank). Questions are, whether this "heat pipe" effect can develop and if so, the nature and scale of the effect. Even if the "heat pipe" effect is not significant, the effect of temperature in lowering infiltration rates needs to be investigated.

Density effects have only been investigated to a limited degree (Ward et al. 1997). These studies did not fully investigate the interactions of density with temperature, unstable flow effects, structurally controlled preferential flow (e.g., clastic dikes), colloidal transport, and/or waste-soil chemical and physical effects to determine inter-relationships and importance among the processes.

C.6.4 Geochemical Processes

As discussed in detail in Appendix H, Applied Science and Technology Plan (DOE-RL 1998b), the Groundwater/Vadose Zone Integration Project realizes that more studies are needed to improve the knowledge and databases for the vadose zone. Regarding geochemistry, it is planned (for both field studies of representative contaminated sites) to improve the conceptual models for waste interactions and contaminant transport processes, and directed laboratory research studies to elucidate chemical processes in greater detail. Geochemists will also help develop a credible reactive transport model. At the present time, the SAC (Rev. 0) will likely rely on the K_d construct to describe all chemical reactions/processes. More sophisticated descriptions of contaminant/sediment interactions may be required for future iterations of the SAC.

Both field studies to characterize the "near-field" geochemical environments at representative inactive liquid waste disposal sites and past leaks at SSTs and complementary laboratory studies under more controlled conditions are planned. The field studies (vadose zone geochemical and hydrologic characterization) will provide the ranges of conditions and field-scale observations on contaminant distributions and migration rates versus time or volume discharge. Once the field characterization data bound the conditions and define the nature and extent of the near-field, laboratory tests can be chosen to better elucidate/quantify the physical and chemical processes that control the interaction of contaminants and sediments. Currently at most liquid disposal sites, information is available on the chemistry and volumes disposed, and groundwater monitoring data are available to describe existing contaminants within the upper unconfined aquifer. The vadose zone is not well characterized in a quantitative fashion.

Field studies will corroborate lab tests and extend the time to study reactions from months to tens of years. Field studies will allow some key questions to be addressed (i.e., the extent of existing physical, chemical, and mineralogic associations between contaminants and major chemical compounds in the waste and sediments and identifying the primary processes that formed the associations). Such "forensic" characterization will identify migration profiles (transport distances and concentrations) of key constituents and changes in the mineralogy, sorption selectivity, and buffering capacity. Once characterization is providing data, laboratory testing to quantitate the key controlling processes will begin. The goal will be to evaluate the key short- and long-term processes controlling the key risk driving contaminants. Processes to quantify likely will include adsorption, mineral precipitation and dissolution, biomineralization, matrix diffusion, pore plugging, and colloid formation and transport.

The emphasis will likely focus on the "extreme-pH" chemical environments for acidic process liquids and highly alkaline tank liquors. The latter were also high temperature fluids, and both are known to have contained organic complexing agents. Our knowledge base is most sparse for these extreme pH wastes that are far from chemical equilibrium with the sediments, which act as a strong buffer. During the buffer process, large amounts of mass dynamically react (dissolve and precipitate minerals). The large changes in mass in solution and mass formed as solids also influences the pore structure and hydraulics (permeability) of the vadose zone sediments. The formation and sequestration of colloids may also be most active in this dynamic zone. It is this highly interactive near-field zone that merits detailed study to improve on the simplistic K_d construct. More detailed discussions of the planned field characterization and focused laboratory studies can be found in the Project Specification (DOE-RL 1998b) and individual project work plans (i.e., the ORP's RFI/CMS Single-Shell Tank Vadose Program Work Plan and the Immobilized Low-Activity Waste Multi-year Statement of Work).

C.7   PROPOSED PATH FORWARD

The integrated knowledge from previous studies and ongoing work provides a reasonable conceptual understanding of the controls on contaminant movement and distribution within the vadose zone of the Hanford Site. However, there are still many outstanding issues, some of which will require additional study, and some of which may only be partially resolved.

Appendix C – Vadose Zone Conceptual Model

C.7.1 Important Components of the Vadose Zone Conceptual Model for SAC (Rev.0)

In accordance with Swift et al. (1999), the conceptual model for the vadose zone consists of three primary components: 1) features (the structure and transport properties of the various pathways); 2) events (e.g., source releases, recharge, etc.); and 3) processes (the fate and transport processes/mechanisms, including driving forces). The use of this structure allows users to clearly articulate those components of the model that are most critical, and it provides a framework within which users can add (or remove) individual components as our knowledge of the vadose zone grows.

C.7.1.1. Features. The physical structure (e.g., geology, hydrologic properties, geochemical properties) of the vadose zone and its principal transport pathways varies by location on the Hanford Site. Other features of the vadose zone conceptual model (e.g., climate and weather statistics, terrestrial ecology, and projected land use) have not been specifically discussed. However, some aspects of the climate and weather phenomena are discussed as they relate to precipitation, runoff, and infiltration events and processes.

Those sites away from the river (i.e., outside the zone of river stage influences [bank storage]) or where significant saturated flow and/or lateral spreading and overlapping/mixing of plumes does not occur (e.g., dry waste burial), or where principal risk drivers are not involved, might be best portrayed by a 1-D stratified soil column. Those sites near the river, particularly near critical habitat or where significant lateral flow and risk drivers are present may require additional detail supported by 2-D or 3-D soil columns.

Because the geometry and configuration of various hydrostratigraphic facies and heterogeneities cannot be adequately portrayed, the effects of these features will most likely have to be captured via sensitivity or uncertainty analyses, within the context of the larger hydrostratigraphic units. Not accounting for small-scale stratifications and variations in texture will likely lead to an underestimation of lateral spreading and either overestimating or underestimating of the predicted penetration depth/rate. For example, sloping layers may increase lateral spreading, but may also reduce travel time to the aquifer by concentrating (funneling) the flow.

With only limited site-specific data, values for the hydraulic properties will have to be estimated from grain-size data, pulling from existing hydrologic property values (Khaleel and Freeman 1995a). This approach also assumes that the relationships between moisture content, pressure head, and unsaturated hydraulic conductivity are nonhysteretic, and can be represented by those of van Genuchten (1980) and Mualem (1976).

Again, without detailed site-specific geochemical data, values for the geochemical properties (i.e., K_ds) will have to be estimated from the sediment type (e.g., grain-size data and the presence of secondary mineralization like the iron oxide coatings often found in the Ringold Formation) and waste type, based on data from existing laboratory measurements. Where high concentration, alkaline, or acidic wastes have been discharged, some form of time-varying change in mobility must also be accounted for. This might be accomplished using a multitude of different K_ds to represent the sorptive capacity of the soils as the waste becomes more diluted and/or buffered by meteoric recharge and waste sediment interactions (i.e., mimicking the

decrease in competing ions along the flow path) as was done in the Composite Analysis (Kincaid et al. 1998). Another option in some critical cases may be fully reactive transport (provided data can be obtained to adequately characterize the controlling features and processes).

C.7.1.1.1. 100 Areas. Features that should be considered in the SAC conceptual model of the 100 Areas include the following:

- At least two hydrostratigraphic units (Hanford formation gravels and Ringold Unit E)

- Continued downward migration of contaminants from source areas and from contaminated vadose zone sediments

- Contamination zoning within the old water table mounds

- Seasonal and diurnal river fluctuations that raise the water table into contaminated sediments contributing to their release from the vadose zone

- Location of the Hanford gravels - Ringold Unit E contact.

C.7.1.1.2. 200 West Area. Features that should be considered in the SAC conceptual model of the 200 West Area include the following:

- At least six hydrostratigraphic units over cumulative thicknesses ranging from 50 to 80 m

- Preferential pathways, including interconnected clastic dikes in the Hanford formation (more frequent in the fine-grained facies), foreset cross bedding in the Hanford formation coarse-grained facies

- Moisture retention within the Early Palouse Soil

- Vertical flow along fractures and/or lithologic discontinuities within the reactive Plio-Pleistocene (caliche) unit

- Lateral spreading along multiple strata with contrasting physical properties (e.g., bedding contacts). This is particularly prevalent (every meter or less vertically) within fine-grained facies and/or paleosols of the Hanford formation, but also occurs atop the Plio-Pleistocene unit, and atop silt and/or clay lenses within the Ringold Formation.

C.7.1.1.3. 200 East Area. Features within the 200 East Area that should be considered in the SAC conceptual model include the following:

- At least five hydrostratigraphic units over cumulative thickness of up to 100 m

- Preferential pathways including interconnected clastic dikes in Hanford formation (more frequent in the fine-grained facies), foreset cross bedding in the Hanford formation coarse-grained facies

- Lateral spreading along multiple strata with contrasting physical properties (e.g., bedding contacts). Particularly prevalent within the fine-grained facies, lenses, and paleosols in the Hanford formation, but also atop silt and/or clay lenses within the Ringold Formation

- Sublinear to anastamosing channel cut scour and fill features within the Hanford formation, which could act as preferential pathways in the horizontal direction

- Tilted beds of the Ringold Formation. Beds dip gently to the south (slope = 1.1 degrees). Angular unconformity exists with the overlying horizontal beds of the Hanford formation.

C.7.1.1.4. 300 Area. Features that should be considered in the SAC conceptual model for the 300 Area include the following:

- At least three different hydrostratigraphic units, including sand-dominated Hanford sediments, gravel-dominated Hanford sediments, and gravel-dominated Ringold sediments

- The presence of silt stringers, particularly in the Hanford formation, although the location and extent of these stringers is uncertain

- At least some degree of heterogeneity and anisotropy in each unit however, again there is insufficient data to adequately portray these characteristics
- While natural short circuiting flow paths (e.g., clastic dikes, fractures, etc.) are not expected to be significant in the 300 Area, preferential flow along well casings or other engineered structures, or as induced by flow instabilities, may be important and should be addressed on a case-by-case basis.

C.7.1.2. Processes. The conceptual model of the vadose zone for the SAC (Rev. 0) should consider the following processes:

- Nature and quantity of contaminants released intentionally and unintentionally to the vadose zone

- Nature and quantity of contaminants retained (stored) within the vadose zone

- Mechanisms, rates, and routes by which contaminants move (or are moved) through the vadose zone to the water table

- Fate of contaminants within the vadose zone.

For the majority of contaminants, movement through the vadose zone is contingent on being dissolved within flowing water. The primary source of flowing water is precipitation that has infiltrated below the zone of evaporation and the influence of plant roots. Such water eventually

flows to the water table, carrying with it whatever dissolved species may be present. Other important transport mechanisms may include gaseous transport, temperature gradients, and possibly colloidal transport.

The rate of recharge at a particular location is influenced by climate, soils, vegetation, topography, springs and streams, animal activity, fire, water and wind erosion and deposition, plant community changes, disturbance, and human structures (e.g., roads; buildings). For many applications, flow rates through the vadose zone can be calculated using Richard's equation with gravity and capillary potential gradients. When these assumptions are not appropriate (e.g., organic liquids, vapor flow, hot saline tank waste, dense liquids or gases), more sophisticated equations must be used to calculate rates.

The formation of colloids and occurrence of colloid-facilitated transport of contaminants were identified by the Expert Panel as a potentially important process for the vadose zone (DOE 1997). For most waste sites at the Hanford Site, the low water contents and simple geochemistry are not conducive to colloid formation or colloid-facilitated transport. However, for the large-volume discharges and the leaking tank wastes, the conditions existed for both colloid formation and colloid-facilitated transport. However, little or no data exist at the Hanford Site to adequately characterize the potential for colloidal transport under these conditions.

Various preferential pathways (e.g., clastic dikes, fractures) are capable of concentrating or contributing to phenomena such as fingering and funnel flow. Because of the nature of some wastes, the local routes of contaminant movement will vary. The Vadose Zone Expert Panel (DOE 1997) stated that the likely mode of transport for leaked or disposed tank waste in the Hanford geology is along preferential, vertical, and possibly tortuous pathways. They identified possible preferential flow caused by the following:

- Hot (350°F) caustic tank waste leaking into the vadose zone, flashing to steam, fracturing the matrix, and enlarging pores

- Hot (350°F) caustic tank waste leaking into the vadose zone with a self-healing nature, creating geothermal convection systems that could move contaminants upward as the hot alkaline slurry reacts with Hanford Site sediments

- Dissolution of siliceous sediments by the hot and alkaline tank wastes, which could increase porosity in some places (by dissolution) and lower porosity in others (by precipitation).

The fate of contaminants in the vadose zone depends on geochemical conditions, the speciation of the contaminant, residence time, and microbial activity. Sediments have the capacity to sorb most contaminants from solution. The amount of sorption is a function of many factors. Some contaminants do not sorb at all. Sorption can be described using a simple linear relationship (i.e., a distribution coefficient or K_d) that is determined empirically. The K_d approach is applicable for most analyses at the Hanford Site where contaminant concentrations are low and the chemistry is simple. However, conditions near some waste sources are so strongly influenced by the chemistry of the waste that the K_d approach may not be applicable. The general consensus is that these wastes will likely decrease the sorption of normally sorbed contaminants (e.g.,

cesium-137), increasing in their mobility until concentrations in the sediments decrease to the range appropriate for the K_d approach.

Contaminants that exist in the gas phase (e.g., radon, carbon-14, carbon tetrachloride) are subject to atmospheric venting and vapor extraction. Carbon-14 as carbon dioxide also reacts strongly with alkaline earth cations to form insoluble carbonates at neutral to basic pH values, and can also react rather irreversibly with cement (Krupka and Serne 1996, Serne et al. 1992). Contaminants near the soil surface are subject to animal and plant uptake and dispersal within the aboveground environment. Contaminants can also be consumed by microbes, degrading into other compounds that may or may not be considered contaminants. Sometimes it is the water that is consumed rather than the wastes. Waste forms such as the ILAW undergo a corrosion process that consumes water. In a dry disposal, this consumption process will create a water vapor gradient that draws vapor toward the waste form.

C.7.1.3. Events. Various events that may be considered in the SAC (Rev. 0) conceptual model include those that are naturally occurring (e.g., meteoric recharge), those that are man-made (e.g., intentional or unintentional contaminant and water releases), those that are rather normally occurring (e.g., occur slowly over a long period of time), and those that represent extreme or unusual occurrences (e.g., 500-year storms, volcanism). Some the important types of events that could be considered include the following:

- Recharge Events (Meteoric, Permitted Discharges, Unintentional releases)
- Source/Release Events
- Discharge/Exit Events
- Climate Events
- Volcanism
- Flooding Events
- Human Disturbance Events.

C.7.2   Options for SAC (Rev. 0)

The behavior of contaminants through the vadose zone is very complex and subject to many unresolved issues and levels of uncertainty. The options for numerically simulating this behavior can be equally as complex. Table C-7 attempts to summarize some of the important features and processes that can be incorporated into the simulations, depending on the complexity of the model.

Table C-7. Options for SAC (Rev. 0).

Model Type	Dimensions & Hydrogeology	Transport Processes	Scale & Temporal Factors	Degradation & Decay Processes
Simple	• 1-D • 4 to 6 Horizontal Layers • Homogeneous, Isotropic	• Aqueous Phase Transport • Linear Sorption Isotherm (K_d) • 4 rads, 2 chemicals, 4 waste types	• Step-Wise Steady State • One Site per area per waste type • Near term (1,000 years)	• Radioactive Decay • Biological Psuedo-Decay
Semi-Complex	• 2-D • Up to 10 Sloping Layers • Homogeneous, Isotropic	• Density and Temperature Effects • Linear Sorption Isotherms (K_d s) • Peak Arrivals • ~10 rads, ~4 chemicals, ~8 waste types	• Long-Term Climate Changes • Sites on 375- x 375-m grid (same as GW) • Near and long term (peaks only)	• Radioactive Decay • Biological Decay
Complex	• 2 & 3-D • Numerous complexly formed layers • Heterogeneous and Anisotropic • Preferential Flow paths • Chemically enhanced permeability	• Multiphase Transport • Colloidal Transport • Barometric Effects • Reactive Transport • Wind and Water Erosion • Numerous rads, chemicals, and waste types	• Episotic, Seasonal Variations • Long-Term Climate Changes • Scale onsite basis • Near and long term	• Radioactive Decay • Biological Decay • Inorganic Decay (Oxidative/ Reductive)

C.7.3 Preferred Alternative

Keeping in mind that one of the purposes of the initial SAC (Rev. 0) is to demonstrate that an assessment of the scale and scope of the Hanford Site and the Columbia River can be conducted, and due to the computational complexity of the more complex modeling options, the simplest model approach was selected for this initial demonstration. The large scale and complexity of a cumulative effects assessment for the entire Hanford Site (particularly the initial assessment [i.e., SAC Rev. 0]), together with the lack of detailed characterization data and/or understanding of some of the detailed fate and transport processes, necessitates simplification of the site features, release events, and the contaminant fate and transport processes.

Implementation of this simpler modeling approach is schematically illustrated in Figure C-15. Inputs to the model would come primarily from the inventory and release elements, including the mass flux and concentrations of the selected constituents as released by the selected waste type. Other inputs include the effectiveness and timing of remedial actions that might either reduce the mass and/or concentration of contaminants in the vadose zone, or might reduce the flux of deep infiltrating moisture (i.e., capping). Assumptions on the amount of precipitation and other climatic factors that would affect deep infiltration would be developed in concert with the other

technical elements (e.g., release element). Definition of the hydrostratigraphy (and the associated hydrologic and geochemical properties) of the 1-D soil column would be based on existing geologic, soil physics, and geochemical databases. K_d values would be selected based on the soil type, waste type, and modeling/simulation results that best match existing vadose zone plumes in both the near, intermediate and far field (recognizing the effects of highly concentrated complex waste chemistries on the mobility of contaminants). To facilitate sensitivity and uncertainty analyses, probability distribution functions will be developed for each primary transport parameter.

The primary transport pathway to be simulated is through the porous media of the vadose zone, and by aqueous phase transport. Some radiological and microbial decay can be simulated using first order decay models.

This preferred approach, while still being further developed, was selected to enable rapid feasibility testing of the SAC (Rev. 0). This approach focuses on a subset of the full general conceptual model for the vadose zone, but does cover a significant range of the contaminants of concern, the types of waste they may be released from, the various hydrogeologic settings of interest, and the physical and geochemical behavior of the contaminants.

Figure C-15. Preferred Approach for Modeling Contaminant Transport Through the Vadose Zone for SAC (Rev. 0).

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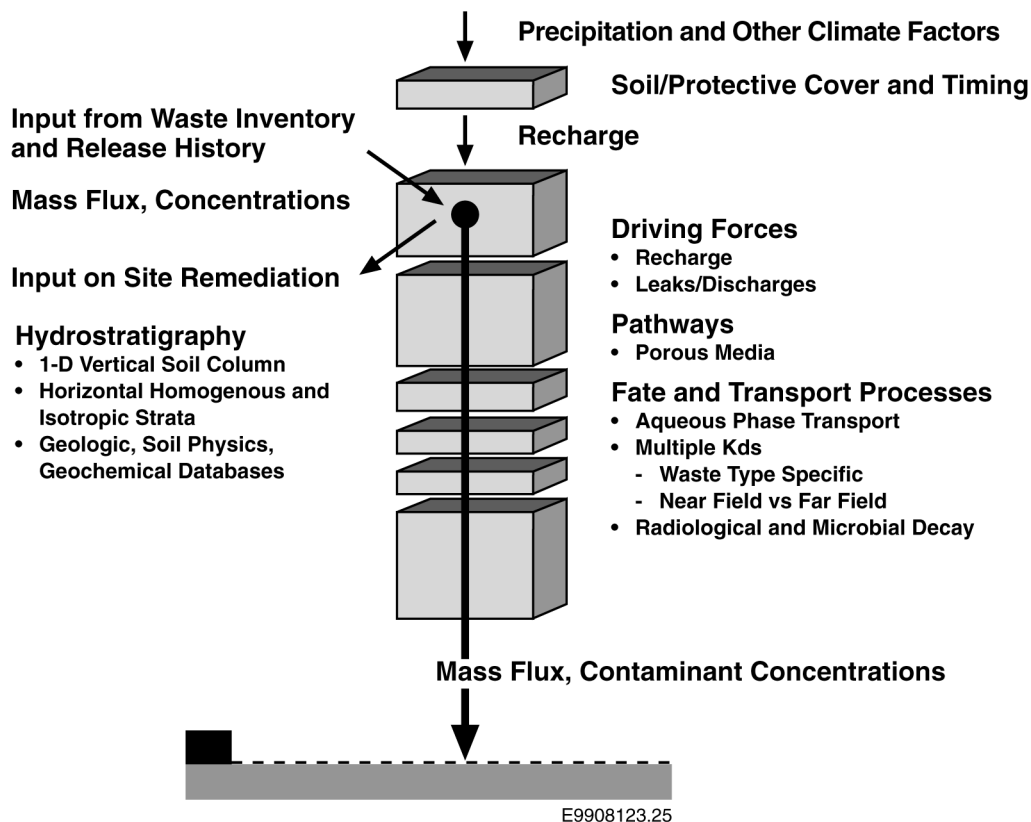
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Appendix C – Vadose Zone Conceptual Model

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